EFFECT OF ROOTS AND TILLAGE ON SOIL EROSION ON A WEATHERED HAWAIIAN SOIL WITH LOW ERODIBILITY

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John S. Coats

Thesis Committee:

James Fownes, Chairman
Samir El-Swaify
Goro Uehara

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Agronomy and Soil Science.

THESIS COMMITTEE

James H. Fownes
Chairman

Goro Uehara

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ABSTRACT

Sustainable farming of marginal lands in the tropics is partially constrained by destructive effects of soil erosion. One farming system proposed for controlling erosion on steep lands is alleycropping, in which crops are grown between parallel hedgerows of trees or shrubs. This study was originally designed to evaluate the mechanisms by which alleycropping could reduce erosion on a steep slope.

The site was located on Kauai, Hawaii, on a steep slope (40%) of a soil classified as the Halii series, an Anionic Acrudox. A preexisting thick vegetation of ferns and shrubs was cleared by bulldozer and subsequently disked twice and hand-raked. Twelve plots, 3 replications of 4 treatments (bare, monocrop, and 2 variations of an alleycrop) were installed on 16 by 4 m plots surrounded by steel sheet metal. Runoff and sediment was collected and measured from each plot for 1 year.

However, soil loss and runoff were not related to treatments, occurring only on 2 plots (Plots #11 and #12) despite several heavy storms. Total runoff and soil loss were 1.1% of rainfall and 0.7 T/ha and 1.9% and 27 T/ha for Plot 11 and 12, respectively.

Fine root content, tillage and exposure, and mineralogy of the soil were investigated to explain these results. Disking and raking had created a well aggregated highly porous, and friable soil structure with high infiltration rates. Exposure and drying of the soil apparently allowed its structure to remain very stable and resistant to structural and aggregate disintegration under the force of raindrops. The two plots with runoff were apparently disked to a shallower depth, thus limiting these effects of tillage and exposure on the soil structure. Very high fine root content in Plot 11 bound soil aggregates together and reduced soil loss in this plot despite significant runoff. A sharp increase of halloysite content correlated with an increase of runoff and soil loss, but was believed to have affected chiefly only runoff.

This highly weathered tropical soil was resistant to erosion, but the demonstrated high spatial variability in prior vegetation, clearing, tillage, and mineralogy, must be taken into account in designing future research in tropical farming systems.

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I. INTRODUCTION

Farming on steep sloping sites and other marginal lands is very common in tropical regions and is becoming more widely practiced as growing populations are making greater demands upon such lands. Farmers have historically relied on traditional cropping systems on these lands, most notably, shifting cultivation. Many traditional shifting cultivation systems which have been fairly stable, sustainable, and effectively controlled soil erosion require long fallow periods and large land areas. With increasing demands upon the land, farmers are no longer able to maintain productivity. In many cases, fallow periods have ceased to exist, and the land is farmed continuously until its productivity is so low the farmer simply abandons a degraded hillside. Although the decline in productivity is most often attributed to declining soil fertility, increasing weed competition, and increased pest infestation, soil erosion often also becomes a serious problem.

Erosion is particularly a serious and rapidly growing problem in the tropics. Constant warm temperatures allow farmers to cultivate year round where water is available. In addition, erosivity in many areas of the tropics is higher than in temperate zones. Annual rainfall in the tropics is usually distributed over shorter periods of the year, rainy season often being a very distinct season. Tropical rainstorms also tend to be more intense and frequent (Hudson, 1971; Kowal and Kassam, 1977; Wilkinson, 1975). Continuous cropping generally requires increased weeding, burning, and disturbance of the soil. This in turn kills roots, stumps, and seedlings on the site. Thus, the capacity of the site to revegetate to a forest quickly is greatly reduced, the bare soil is exposed to raindrop impact for long periods of time, and the potential for the soil to erode is subsequently greatly increased.

Increased cultivation of these marginal lands has necessitated work to develop alternate and sustainable cropping systems which require less land area. There are many requirements for a cropping system to be sustainable. On steep sloping sites, it will be particularly important that the system controls erosion.

Alleycropping with perennials has popularly been promoted in recent years as an alternate sustainable cropping system in the tropics on sloping sites. This cropping system is similar to a typical continuous cropping system but one in which trees have been closely planted as a hedge in rows that run along the contours of the slope. Hedgerows are separated by an "alley" where crops are grown. The trees are periodically lopped off to a low height, about 1 meter or less, and the residue then applied to the crop site, used as a nutrient amendment to the soil or a cover mulch. In some cases this residue is removed from the site as fodder for livestock or as fuel wood.

There are numerous claims and suggestions about the advantages of alleycropping. One of these has been that alleycropping controls soil erosion, enough to allow long-term and continuous cropping of such sites (Kang et al., 1986; Laquihon and Watson, 1984). However, to date there is very little scientific data and research to verify this claim, particularly in regard to steep slopes. The objective of this research project was to examine the effect of alleycropping on soil erosion. The proposal asked the two following questions:

1. Does alleycropping with perennials on a <u>steep</u> slope reduce erosion?
2. If so, what are the mechanisms involved that reduce erosion?

The soil loss results of this study, however, did not provide any new data or information relevant to the purpose of the study. In fact, soil loss appeared to be completely unrelated to any treatments. The objective of the final thesis became simply to explain as much as possible the actual results of soil loss and runoff, the pattern of which is depicted in Figure 1. The pattern indicates that soil loss and runoff was very unlikely due to an effect of treatment. Specifically, the questions then became:

1. Why was there no runoff or soil loss on Plots 1-10 and considerably less on Plots 11 and 12 than would be predicted by the USLE model?

2. Why was there considerable runoff on both Plots 11 and 12 when there was none on Plots 1-10?

3. Why was there such greater soil loss, and runoff to a much lesser extent, on Plot 12 than Plot 11?

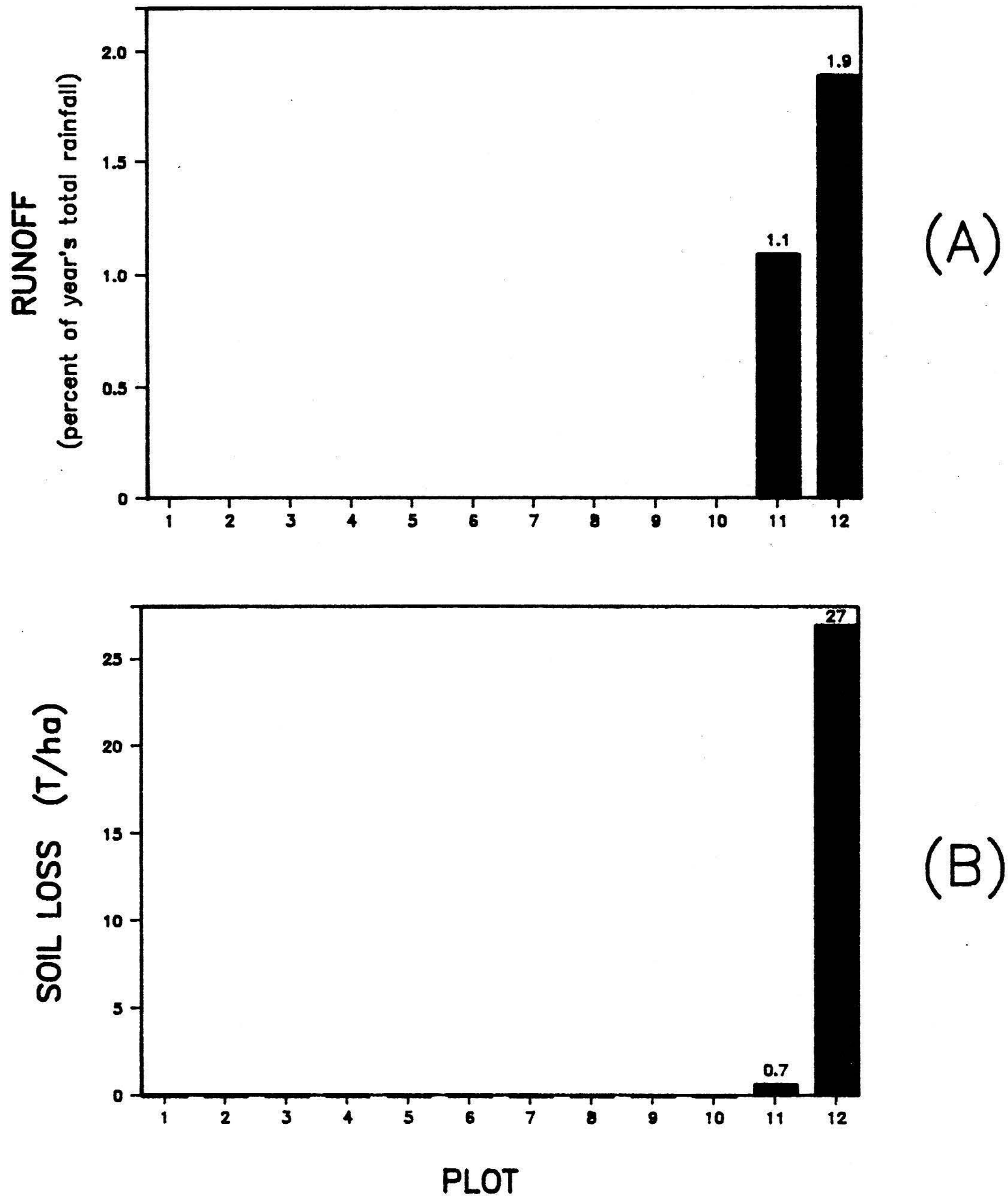


Figure 1. (A) Total runoff and (B) soil loss for experimental period (1 year).

II. APPROACH

A. Approach of Original Study

The study was conducted on a site with high annual rainfall and a relatively steep slope, an environment where soil erosion losses are potentially high. The soil was a highly weathered and infertile soil, simulating less than ideal growing conditions often associated with marginal lands in the tropics.

It is already known that surface soil cover is a very good method for controlling soil erosion. Terracing of steep slopes breaks up slope length and can also be an effective method for controlling soil erosion. It was hypothesized that alleycropping could reduce erosion on steep slopes by one or more of the following mechanisms:

1. Closely planted stems of trees in a contour on the slope act as a semipermeable barrier to sediment and plant matter, causing them to collect along this barrier and form a terrace. This will reduce runoff velocity, trap sediment, effectively reducing the continuous length of the slope.

2. By placing the cuttings of the trees at the base of the hedgerow stems on the uphill side parallel to the slope contour, the barrier and terrace effect will be enhanced.

It is possible that the stems by themselves are inadequate for controlling soil losses and may in some cases actually exacerbate the process because stems will force the flow of water to narrow between the stems, increasing its velocity and force.

3. Residue as tree loppings of branches and particularly leaves act as a direct protective cover of the soil surface from raindrop impact, lengthens the tortuous path of runoff, and blocks the path of particulate flow, increasing soil deposition.

4. Some researchers also suggest low canopies of trees will reduce erosion by intercepting raindrops or decreasing the velocity at which they strike the soil (Hudson, 1957; Elwell and Stocking, 1976; Othieno and Laycock, 1977).

B. Experimental Design of Original Study

The experimental design consisted of 4 treatments in a completely randomized design: a nonperennial continuous cropping system, two variations of an alleycrop system, and a bare fallow treatment. In one alleycrop treatment the loppings were removed and in the other the loppings were retained on the site. The standard bare treatment is similar to but not a true standard USLE fallow unit plot. It serves as a control. The bare treatment was prepared in the same manner as all other treatments. All 3 cropped treatments had the same annual crop and sequence. There were 3 replications, thus 12 total plots. Soil loss and runoff was collected off each plot.

C. New Approach

The approach in the field to find answers was fairly simple. The plots and soils were studied and observed visually. Apparent variations in vegetation, surface cover, soil properties, and other variables which were thought to possibly affect soil loss and runoff were noted. Those variables were analyzed and quantified in some way to determine if they correlated with runoff or soil loss. In addition, a few factors which were suspect because of their already known effects on soil loss or runoff were also examined. Often, cursory preliminary data was first taken simply because the site is very large and the number of variables that could have been examined was numerous. This was desirable to avoid excessive expense, time, and labor of conducting an extensive analysis of a variable which did little to explain the results.

Although it is not assumed that Plots 1 through 10 are all alike, the pattern of runoff and soil loss suggested they were sufficiently enough alike that for whatever reason Plot 10 did not have runoff or soil loss, the same might well be true for the first 9 plots. Because the site is so large and since there is such a strong gradient in runoff and soil loss from Plots 10 through Plot 12, it was much simpler and more economical to concentrate many of the analyses on this much smaller area. One obvious criticism of this approach of course is that it assumes that lack of runoff and soil loss for Plots 1-10 is due to common variables and ignores the possibility that runoff did not occur on Plot 1 for different reasons it did not occur on Plot 10. To minimize such a mistake, data was sometimes taken from the entire number of experimental plots. When this was not done, the reason for not doing so was generally because the data did not strongly suggest that that variable was important or that adequate analyses for all plots would be particularly expensive or laborious.

It should be emphasized that the experiment was set up and designed to accomplish the original objective of studying the effect of alleycropping on erosion. The final thesis however concentrates on explaining data results which have no relation to alleycropping or the original treatments. Subsequently, there have been many problems in how to take samples and how to analyze the data. The experimental design and repetitions are no longer useful. If we were to distinguish new treatments according to the amount of runoff and soil loss, there would in effect be three treatments: Plot 12, Plot 11, and 10 plots of a treatment with no runoff.

D. Using the USLE Model as a Working Framework

In analyzing the data to explain sediment losses, it was useful to group the various parameters analyzed into categories to provide a useful framework for analyses and discussion. The Universal Soil Loss Equation (USLE) and its various components proves to be a useful tool for this purpose. The USLE equation, developed by Wischmeier and Smith (1978), is as follows:

$$A = R * K * L * S * P * C \qquad [1]$$

where A is equal to soil loss in metric tons per hectare and each additional letter is an index of a factor that effects soil loss.

R = rainfall and runoff factor in kNewton/hour;
K = soil erodibility factor in T/ha per erosivity unit;
L = slope length factor (dimensionless);
S = slope gradient factor (dimensionless);
C = cropping and management factor (dimensionless);
P = erosion control practice factor (dimensionless).

In the USLE model then, components are additive, small component values contribute to less soil loss, and greater values to greater soil loss. This equation was specifically developed to predict soil loss due to sheet and rill erosion on agricultural sites and developed from data of U. S. temperate soils (Wischmeier and Smith, 1978). Attempts are currently being made to extend the model to include forests, rangelands, and even urban and construction areas (Wischmeier, 1976; Dissmeyer and Foster, 1980). It is commonly used in Hawaii both in research and in predicting long-term soil loss (Soil Conservation Service, 1976; Dangler et al., 1976). Although it is not necessarily meant to accurately predict soil loss for short-term periods, with careful determination of appropriate index values it has been used in this manner experimentally and should serve as a useful tool in identifying key parameters in this experiment.

1. R Factor

The R factor is a measure of the erosive power of rainfall. Soil loss has been found to be directly proportional to erosivity when all other factors are held constant. Erosivity is readily estimated by an empirical function of rainstorm kinetic energy and maximum intensity.

The impact of a raindrop causes splash erosion and its force increases as the kinetic energy of the raindrop increases. Kinetic energy of a raindrop increases as either raindrop size or velocity increase (Ellison, 1944; Ekern, 1951; Bisal, 1960). Very high correlations have been found between raindrop kinetic energy and splash erosion (Mihara, 1952; Free, 1960).

Larger storms not only have greater kinetic energy but are more likely to saturate the soil, producing runoff and further increasing soil loss. Because soils are nearer saturation during a rainstorm, the rate of runoff and thus soil loss are very sensitive to the maximum intensity of the storm as this is the point when rainfall intensity will most likely exceed infiltration rates. Wischmeier and Smith (1978; Wischmeier, 1959), following up on the work of other researchers, have developed an empirical method for estimating the erosivity of a rainstorm which has been found to correlate well with soil loss in the mainland United States. The method estimates a rainstorm's kinetic energy from 30-minute intensity segments and multiplies this value by the maximum intensity of the storm to obtain an index, thus taking into account both the kinetic energy of a storm and its potential to cause runoff by exceeding infiltration rates. This index has been shown to be very applicable for Hawaii (Lo et al., 1985).

Erosivity for this experimental site for the period studied has been calculated using Wischmeier and Smith's index to be 1980 kN/h. The specific method of calculating erosivity is provided in Chapter 4.

2. K Factor

The K factor is an index of a soil's potential to erode due only to inherent properties of the soil itself, and depends on soil properties such as mineralogy, soil structure, permeability, aggregate stability, and organic matter content of the soil. The K value is best determined experimentally on a standard unit fallow plot where the factors L, S, C, and P are all considered to be equal to 1. K is then equal to the soil loss measured divided by the rainfall index (A/R). A standard unit plot has been arbitrarily designated as one which is 22 m long with a uniform 9% slope in continuous fallow and tilled up and down the slope. Tillage is the equivalent of seedbed preparation for a corn field on the mainland United States. Erosion studies often include a standard unit fallow plot so K can be calculated. The K factor allows comparisons between different soils' erodibility.

The bare plot in this experiment is not a true standard fallow plot. Although the slope and length of these plots are non-standard, the L and S indexes to adjust for non-standard slope and length can be extrapolated. More importantly, the plot was not cultivated in the same way as the accepted method for standard plots. Standard plots are to have been kept free of vegetation for a minimum of 2 years and thoroughly tilled up and down the slope. This was not true of the bare plots in the alleycropping experiment. Thus, the value of C is unknown making an accurate estimate of K for the soil difficult.

Wischmeier et al. (1971) found on eastern United States soils, that particle size distribution, percent organic matter, soil structure, and profile-permeability were parameters of soil properties that could be used to reasonably estimate an accurate K value for a particular soil. Using a nomograph which is based on this data (Wischmeier and Smith, 1978), a value of 0.10 was estimated for this site, assuming organic matter to be 9%, permeability to be moderate to rapid, soil structure to be medium or coarse granular, 55% clay, 10% sand, and 35% silt and very fine sand. This information was estimated from available published data of the Halii soil and measured parameters during the experiment (Ikawa et al., 1985; SCS, 1976). The Halii series soil in this study has been assigned a value of 0.13 by the Soil Conservation Service (SCS, 1981), a value only a little higher than that calculated from the nomograph. The SCS value is a general estimate provided for all soils classified as the Halii series. Initially, we will assume the former value, 0.10 to be accurate.

El-Swaify and Dangler (1976), and others have found though that this model is inappropriate for a range of Hawaiian soils. They found that soil structure and profile-permeability codes used by Wischmeier et al. (1971) were particularly poor predictors and the model's limit of only 4 percent organic matter was an additional problem. Instead, they found that parameters of aggregate stability and mineralogical codes were more useful indicators.

3. L and S Factors

Increase in length and steepness of a slope both increase soil loss because runoff has greater momentum and force, increasing its transport capacity. Equations for both factors have been empirically determined by Wischmeier and Smith (1978) from long-term data recorded from erosion plots in the midwestern United States. The L and S factors are calculated as a relative value to the expected soil loss from a standard unit plot of standard length and slope as described before. The LS factors combined equation is:

$$LS = (L/22.1)^m * (65.41 * X^2 + 4.56 * X + 0.065) \qquad [2]$$

where L is the length of a uniform slope in meters, m is equal to 0.5 if the slope is greater than 5% as in our case, and X is equal to the sine of the slope angle in degrees. However, their data represent only slopes between 3 and 18 percent. The slopes in this experiment are about 40% and require extreme extrapolation if values are calculated from this equation (Figure 2). McCool et al. (1987) recommended a modified model for slopes between 9 and 18 percent that improved the predictability of Equation [2]. Their reexamination of available data revealed that at slopes greater than 9%, soil loss increases more rapidly than at lower slopes because rill erosion begins occurring. They also found that soil loss tends to increase linearly and not exponentially as implied by Equation [2], yet they state that even the revised equation should not be extrapolated to slopes higher than 18%. McCool et al. (1982) proposed a tentative equation for greater slopes based on limited data from field observations and erosion plot data taken on a Palouse soil of slopes of 9-60% in the Pacific Northwest:

$$LS = (L/22.1)^{0.3} * (S/9)^{1.3} \qquad [3]$$

where L is equal to length of slope in meters and S is the percent slope. Equation [2] overestimated soil loss on their steep slopes.

Singer and Blackard (1982) found that the relationship between soil loss and slope varied with soil type, suggesting an interaction between slope angle and soil erodibility. Gregory (1980) found that soil loss due to slope factor changed with bulk density values. Wischmeier, Smith, and other researchers also believe that there is an

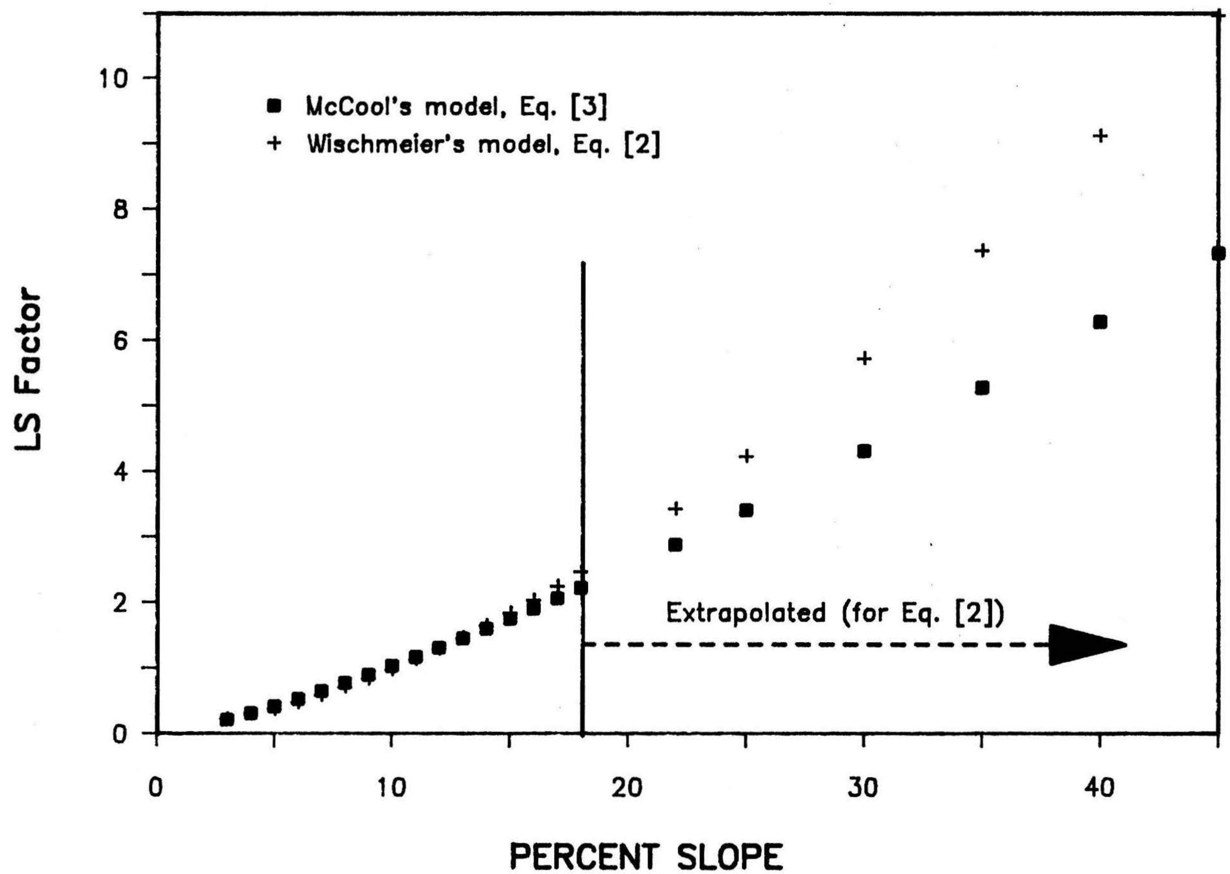


Figure 2. Relationship between LS factor and slope for Eq. [2] and [3] (16 m length).

interaction between slope and erodibility. Wischmeier and Smith (1978) state that even a soil with a relatively low erodibility factor may show signs of serious erosion when it occurs on long and steep slopes or in localities with numerous high-intensity rainstorms.

Length for each plot in this study is 16 m. Slopes vary only slightly from plot to plot and are generally uniform. Since we are less interested in determining "true" accurate values of any of the above factors and are using the USLE equation primarily as a tool to identify specific differences between plots, a true value of the L and S factor is of less importance. To err here will not affect comparisons between plots significantly as slopes vary minimally among the plots. The combined LS values calculated from both Equations [2] and [3] for all plots are provided in Table 1. Values estimated by Equation [3] will be assumed in this thesis because it is based on experimental field data on representative slopes. The data for very steep slopes remains limited.

Table 1. Slopes and combined LS factors as computed by Equations [2] and [3] for Plots 1-12.

		LS Index	
Plot	Slope (%)[a]	Eq. [2]	Eq. [3]
1,2	44	10.6	7.2
3	42	9.9	6.8
4	40	9.1	6.3
5	41	9.4	6.5
6,7	40	9.1	6.3
8	40	9.3	6.4
9	43	10.1	6.8
10	40	9.1	6.3
11	38	8.3	5.8
12	40	9.3	6.4

[a]Slopes were measured with a transit.

4. P Factor

This factor considers soil conservation practices, such as contouring or terracing which reduce erosion. Various practices are generally assigned some value less than 1, but when no practices are utilized, P is generally taken as unity or 1. Although the site was initially disked in a crosswise fashion, all ridges were levelled and made smooth by hoeing and raking. For this study, P is taken as 1.

In any case, Wischmeier and Smith (1978) do not lower the P value for contoured forest soils of slopes above 19%. For unforested soils, they also assume a value of 1.0 for slopes greater than 25%, despite method of tillage. They state that from their experience, contoured very steep slopes usually do not have decreased soil loss, and in fact, often have increased soil loss.

5. C Factor

The cover and management factor (C) is the ratio of erosion expected from a site under management or with vegetative cover of any kind compared to that of a bare standard unit plot with identical R, K, L, S, and P index values. These index values have been obtained from erosion plot studies for various forms of cropping systems in the United States. The C factor is often broken up into smaller and more specific components. Factors have been derived for different crops, different stages in crop growth, type of tillage system, and other characteristics of cropping systems. Efforts are now being made to assign values for forests, grasslands, urban areas, and other nonagricultural sites to extend the usage of the USLE model (Dissmeyer and Foster, 1980).

Unfortunately, this factor includes a very great range of variables since it not only includes vegetal factors such as canopy, ground cover, mulch, and plant matter on the surface, but also includes variation in management. The model fails in universal application perhaps most often because of the lack of appropriate index values for cropping systems outside the United States or for any site with vegetative cover not typical to U.S. cropping systems. Index values must be specific for every cropping system and type of vegetative cover.

This is a serious problem in choosing an appropriate C value when it is considered that numerous studies have shown that good management coupled with high surface cover can reduce soil by as much as several orders of magnitude (Hudson, 1957; Meyer and Mannering, 1971). This is also true of undisturbed forests and grasslands where vegetal matter within, on, and above the surface also have the same effect. Stocking (1988), a researcher who has devoted much of his work to studying the effects of vegetation on erosion in the tropics, states that vegetative cover is second only to rainfall as the most important factor that determines soil erosion. Nevertheless, when appropriate index values have been accurately determined for non-cropland sites with varying amounts of vegetative matter, the model can again become useful.

The plots in this study do not have identical C factors. Plant matter content in the soil appeared to be of a different kind and less in Plot 12 than in most of the other plots. Problems with disking of the Plot 12 end of the field site may also have affected the structure of the soil in that plot. Although soil structure is considered a component of the erodibility factor, management by using different tillage operations can significantly affect the erodibility for certain soils. Because of these problems, initial estimates of an accurate C factor for these plots are at best tenuous.

The preparation and thorough subsequent tillage of a standard plot is considered to expose the soil to maximum potential erosion, and such sites are assigned a value of 1. Any other tillage or cropping practice that alters C is generally assigned a value less than 1. Plot 12 was disked twice roughly along the contour of the slope, but then was extensively raked and smoothed by hand, negating the effect of contouring. Wischmeier and Smith suggest a factor of .64 for cropland soil in fallow on 12-18% slopes that has been shallow disked and harrowed. Assuming that deep disking increases soil loss, but residue decreases it, they assign a factor of .61 to deep-disked cropland sites in fallow of lesser slopes which have a residue of about 2000 kg/ha.

Our site was previously covered with brush and a thick root mat, which was subsequently removed by bulldozing. Some plant matter and rock remained on the surface and numerous roots remained in the A horizon. Wischmeier and Smith (1978) use an alternate nomograph for estimating appropriate C subfactors for cropland sites with higher plant matter, accounting for variation in surface and canopy cover. Using his nomograph, C subfactor values are estimated in Table 2. Wischmeier and Smith (1978) also provide a table of values which assumes a site was woodland but was subsequently disked, raked, or bedded. Values for our plots are estimated from this table and provided in Table 3.

Dissmeyer and Foster (1981) have recently attempted to derive appropriate C subfactors specifically for forest and grasslands. From

Table 2. C subfactor values for mulch and canopy effect on croplands suggested by Wischmeier and Smith (1978).[a]

Plot	Surface cover (%)	Canopy (%)	C value
12	4	10	.88
11	7	0	.85
10	9	15	.70
1-9	10[b]	10[b]	.72

[a]Seedbed tillage and 20" height canopy are assumed.
[b]These are average values of surface cover and percent canopy for Plots 1-9. Values range from 0-15% for canopy, and 6-14% for surface cover.

Table 3. C subfactor values for surface cover effects for woodlands suggested by Wischmeier and Smith (1978).[a]

Plot	Surface cover (%)	C value
12	4	.44
11	7	.39
10	9	.35
1-9[b]	10	.33

[a]Assumed for sites with excellent soil condition prior to tillage, fine root mat was tilled in, and there no longer is any live surface cover. In our case, there were numerous fine roots in the soil, but the surface root mat was removed by bulldozing, and not disked in.
[b]Surface cover is averaged as in Table 2.

previously published literature, experimental data (not provided or cited), and subsequent field observations of forest and croplands by soil conservation agronomists, geologists, forest hydrologists, and agricultural engineers, they have proposed new C subfactor tables for the vegetative parameters affecting soil loss on tilled woodlands. Values derived for our plots from these tables are given in Table 4.

The values provided in Tables 3 and 4 are roughly similar. Values from Table 4 will be accepted to be most accurate because they have been specifically derived for forested areas and grasslands.

Table 4. Vegetative C subfactor values derived from tables proposed by Dissmeyer and Foster (1981) for woodlands which have been tilled.

Vegetative Subfactors	C subfactors for Plots: 12	11	10	1-9
Percent surface cover[a]	.91	.84	.78	.80
Canopy cover	.93	1.00	.88	.93
reconsolidation (6 mo)	.94	.94	.94	.94
root mat on surface[b]	1.00	.97	.97	.97
root binding effect[c]	.60	.43	.43	.43
C factor product:	.48	.33	.27	.29

[a]Percent cover and canopy cover are as in Table 2.
[b]Reamining root mat assumed at 0% and 2% for Plot 12 and Plots 1-11 respectively.
[c]Initial fine root mat, which is tilled in, is assumed to be fair and good for Plot 12 and Plots 1-11, respectively. These tables assume root mats were not removed by bulldozing.

Table 5. USLE factor values initially estimated for Plots 1-12 and predicted soil losses.

Plot	R	K	LS	C	A
1-9	1935	.10	6.6	.29	370
10	1935	.10	6.3	.27	330
11	1935	.10	5.8	.33	370
12	1935	.10	6.4	.48	590

Table 6. Predicted and measured soil loss for Plots 1-12 compared.

Plot	Predicted	Measured	Factor of error:[a]
	-------------T/ha-------------		
1-9	370	.010	37000
10	330	.010	33000
11	370	.73	510
12	590	27	22

[a]Factor of error is defined as predicted soil loss divided by measured soil loss.

Table 5 lists the various USLE factors as assumed in this section and predicted soil loss by the USLE model. Table 6 compares actual and soil loss predicted by these USLE indexes. For Plot 12 and Plot 11, the predicted values are much higher than the actual values, 22 and 507 times higher. Plots 1-10, assuming soil loss to be 10 kg/ha, are 33,000 times higher than predicted. It is obvious that one or more factors are grossly overestimated.

This study focused on those factors which were thought to explain and determine soil loss variations from that predicted. As will be discussed in Chapter 4, measurements of soil loss are considered to be very reliable. The rainfall factor has been measured and calculated according to USLE requirements. The EI30 index's proven utility in Hawaii makes it a fairly confident estimate of erosivity (Lo et al., 1985). There appears to be a linear relationship between soil loss and EI30 for Plots 11 and 12 after runoff begins, indicating that EI30 is a useful erosivity parameter (Figure 3). The erosion control measure factor, P, we know to be 1 because no control measures were utilized. LS indexes have been estimated from an equation with very limited data so it is very possible they are not correct. However, they probably do not vary among plots and it is unlikely that they are lower than 2.5, the unextrapolated index estimated for an 18% slope (by Equations [2] or [3]). Since 2.5 is only about 0.4 of the assumed indexes, then an error in the LS indexes certainly does not explain much of the error in prediction.

The only two remaining factors in serious question are the erodibility factor, K, and the cover and management factor, C. They are

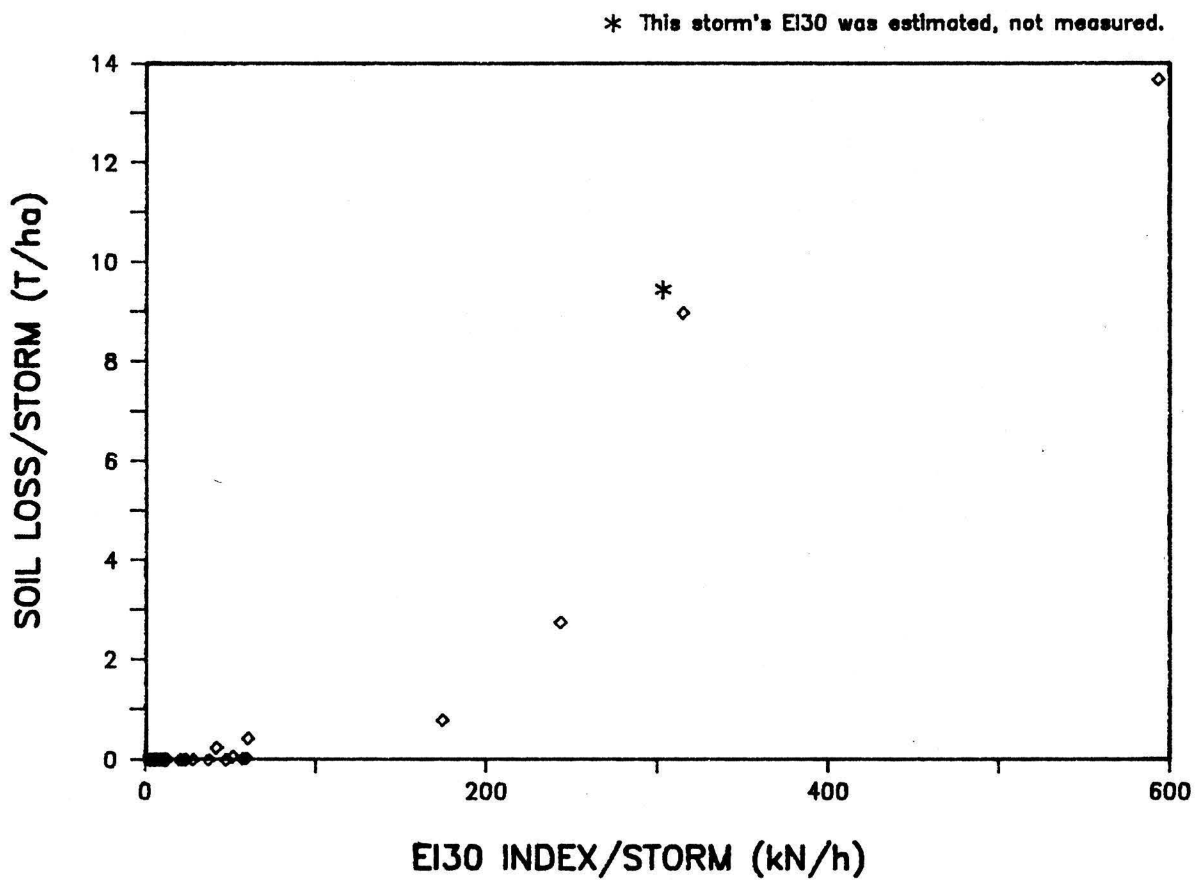


Figure 3. Scatter plot of soil loss/storm vs EI30/storm for experimental period (Plot 12).

Plot 12 Plot 11 Plot 10 Plot 9

Figure 4. Photograph of Plots 9–12 soon after clearing and disking.

primarily suspected of being different from those given in Table 5 and of explaining the differences between measured and predicted soil loss results. This study focusses almost exclusively on variables affecting these 2 factors.

Erodibility is a naturally suspected factor for two reasons. First, it is already known that this soil, an Anionic Acrudox, is fairly resistant to soil erosion. The K value, 0.10, is an estimate, and has not been directly measured on this site. Secondly, the pattern of soil loss strongly suggest that the data is not at all reflective of the treatments but rather that there may be a strong gradient in the soil itself between Plots 10 through 12 (Figure 1). Visual observations of this end of the field before the treatments were installed shows a marked change in the soils's color (Figure 4, p. 23).

The C factor is suspected for two reasons. The plots were not prepared in exactly the same manner. There was a problem in tilling one end of the experimental site (the Plot 12 end) and it is very possible this affected the susceptibility of the plots at this end to erode. Secondly, there was thick vegetation on the site before bulldozing. Residue or effects of previous vegetation on soil structure could well have lowered the C factor. Dissmeyer and Foster (1981) have attempted to apply appropriate C subfactors, but this a difficult task as their data is limited. For example, they identify only two categories of fine root content in the soil which binds the soil, but obviously fine root content varies over a great range. In our study, fine root content is very high, despite the root mat being removed.

III. LITERATURE REVIEW

A. Factors Affecting Erodibility

Wischmeier and Smith's K factor nomograph is based on considerable data from U. S. temperate soils and has proven useful in estimation of the erodibility factor. However, application of the nomograph has not been successfully transferred to many tropical soils. Many weathered tropical soils have been found to have properties which make them less susceptible to erosion than most temperate soils. Dangler and El-Swaify (1976) measured the erodibility for several Hawaiian tropical soils with standard USLE fallow plots. They found for several weathered soils the K factor was exceptionally low, .07-.08 for a Typic Hydrandept and 0-0.16 for a Humoxic Tropohumult. Values of .13 or less on U.S. mainland temperate soils were reported by Wischmeier and Smith (1978) only for soils described as loamy sands or gravelly.

Properties which make these soils less erodible are not adequately accounted for by the empirical parameters used in the nomograph. El-Swaify and Dangler (1976) found low or no correlations between many Hawaiian tropical soils and high clay content, and Wischmeier and Smith's nomograph codes for soil permeability and structure. They found parameters of aggregate properties, percentage of soil in suspension, and mineralogy to correlate much better with a soil's erodibility.

1. Effect of Mineralogy

Weathered tropical soils tend to aggregate well, increasing infiltration rates and reducing actual soil losses. Dangler and El-

Swaify (1976) found that for soils within a given region with similar parent material, increasing rainfall correlated with decreasing erodibility. Beinroth et al. (1974) found that the extent of weathering on the east side of Kauai could also be positively correlated with rainfall. Singh and Uehara (1986) argue that minerals with variable type surface charges, stemming from both van der Waals as well as electrostatic forces, tend to have near net zero charges. Particles of soils of these minerals mutually flocculate because of the attractive forces between opposite charges and lack of dominating repelling electrical charges. El-Swaify (1976) demonstrated that Fe and Al hydroxide colloids of oppositely charged double-layers correlate with aggregate stability diagrams. Hough et al. (1941) had earlier concluded that conventional mechanical analyses of many Hawaiian soils was useless because of their colloidal properties. Weathered tropical soils composed of 1:1 minerals and Fe and Al oxides exhibit these properties. Despite the fact that they are high in clay content, the clay size particles are aggregated into stable units which behave very differently than easily dispersable aggregates composed of 2:1 clay minerals.

2. Effect of Irreversible Drying and Related Properties

Researchers have shown that use of Wischmeier and Smith's nomographs particularly significantly underestimates K values for Hawaiian soils containing considerable amounts of amorphous and oxidic materials (El-Swaify, 1977; Dangler et al., 1975). Schultz (1988) measured the K value of a Typic Hydrandept to be .0008, although Wischmeier and Smith's nomograph estimated K to be .06. Schultz stated that the unusually low erodibility was due to the fact that the soil was very weathered by high rainfall and contained significant amounts of amorphous oxides, resulting in irreversible dehydration properties and high aggregate stability. This lead to high infiltration rates and low runoff.

Consequently, tillage and exposure to drying of soils with irreversible dehydration properties can actually sharply reduce the erodibility of the soil. This is contrary to the effect of tillage and exposure of most temperate soils characterized by predominantly permanent charges. On these soils, tillage temporarily decreases soil loss because the loosened soils have higher infiltration rate, but this is only a temporary state. Storm raindrops quickly break down the aggregates and structure of the soil, rapidly reducing infiltration rates. The now loosened soil is even more susceptible to erosion than before tillage. For this reason, Wischmeier and Smith assign a maximal value of 1.0 for the C factor in the USLE model for soils that are fallowed and have been thoroughly tilled, and lower values to tilled soils. The effect of tillage and exposure of the soil tends to be opposite on soils with irreversible dehydration properties, although Wood (1977) noted that the effect may be an increase in potential erodibility. He argues that during intense storms the large loose aggregates on the surface are now more easily washed away.

Although the term irreversible dehydration is generally associated with plinthite-containing soils and Hydrandepts, other highly weathered tropical soils exhibit properties somewhat similar to that of irreversible dehydration. Barnett et al. (1971) tilled and prepared a

Puerto Rican Typic Tropohumult soil high in clay according to USLE standard fallow criteria, and measured the erodibility to be only .004. Barnett commented that the soil, which behaved more like a gravelly soil, appeared to self-mulch itself with a surface of strong stable aggregates. The aggregates did not break down despite heavy rainfall, and infiltration rates remained high. Water filtered down to the untilled layer and resurfaced farther down plot where the soil was not tilled. Soil losses, which were low, only occurred when the EI30 index exceeded 65 kN/h, despite slopes of 40%. Barnett, however, does not report on the exact method and depth of tillage.

Van't Woudt and Uehara (1961) reported that on a Gibbsihumox soil (located within 1 km of the site of our experiment) also had self-mulching properties. When the soil was exposed, there was a tendency for the formation of a loose, granular surface mulch 2-3 granules thick. Although the Gibbsihumox is described as one with irreversible dehydration properties (Soil Survey Staff, 1961), it should not be confused with the irreversible dehydration properties commonly associated with Hydrandepts or plinthite soils. Keng and Uehara (1973) measured the delta pH of a Halii soil to be less than minus 0.5. Delta pH is taken as equivalent to the surface charge. Thus, the surface charge of the Halii soil indicates that the positive charges on the soil nearly equal the negative charges, allowing for high colloidal and flocculating properties. Ikawa et al. (1985) also measured the delta pH of a Halii soil to be low, minus .39, for the surface layer.

Small particles of gibbsite and goethite that are coated with an amorphous gel-like material cluster and are reported to have irreversible surface crusting and aggregation properties (Jones and Uehara, 1973). Such high aggregate surface soil stability can severely restrict slaking or sealing, even during a heavy rainstorm. The Halii soil has a high content of gibbsite, goethite, and some halloysite (Appendix 2), but probably does not contain considerable amounts of amorphous material.

3. Effect of Halloysite Minerals

In this study, the plot with the most soil loss was measured to have the highest content of halloysite. Halloysite is not considered to be in a final stage of weathering as in the case of gibbsite and hematite. In fact, when desilicated and finally weathered, the Hawaiian form of halloysite is believed to often form gibbsite (Uehara et al., 1966). Halloysite is generally found in less weathered horizons. Van't Woudt and Uehara (1961) found that halloysite increased and gibbsite decreased with increasing depth in a Gibbsihumox. Halloysite is a mineral with a 1:1 matrix like kaolinite but with an inner layer of water molecules. In its dehydrated form, as in this soil, the surface net charge is reduced but is still negative (CEC of 5-10 me/100 g), (Grim, 1953). It is possible that the relatively small negatively charged halloysite particles pack tightly with positively charged goethite, reducing macroporosity. El-Swaify and Dangler (1976) coded minerals common in many Hawaiian soils according to their effect on erodibility. The code estimates that the less weathered halloysite is 5 times as erodible as the more highly weathered minerals, gibbsite and goethite. Why halloysite increases erodibility is not well understood.

4. Effect of Soil Organic Matter

Wischmeier (1966) found that soil organic matter explained 45% of the variability of the K value in extensive erosion studies on 35 U.S. mainland soils. Ram et al. (1960) found aggregate stability to be correlated with organic matter when studying the effects of cover crops on soil physical properties. Many early researchers had suggested that polysaccharides act primarily as bonding agents between organic matter and soil particles (Martin, 1946; Greenland et al., 1961; Greenland et al., 1962). But Mehta et al. (1960) found that exclusively removing polysaccharides from synthetic and natural aggregates did not produce identical results, indicating that at least one more bonding agent was involved. Other researchers (Aringhieri et al., 1978; Geoghegan et al., 1947) also found inconsistencies between stable aggregates and polysaccharides.

Hamblin et al. (1977) found that aggregate stability was more highly correlated with removal of both polysaccharides and iron and aluminum oxides than with either component separately. Organic matter is now believed to coat inorganic soil particles. Soil organic matter has very high cation exchange capacities, 150-300 me/100 g of soil (Bohn et al., 1985). These high negative charges attract organic particles to minerals with opposite charges, increasing soil aggregation. At lower pH values, goethite and to a lesser extent, gibbsite and hematite, are characterized by net anion exchange capacities (predominantly positive charges on the surfaces).

B. Effect of Vegetal Matter on Soil Loss

1. Roots

The literature concerning the direct effect of roots in the soil on sheet and rill erosion is limited, although there are numerous studies where researchers have found that diameter and quantity of live roots positively correlate with root shear strength (Ziemer and Swanston, 1977; Burroughs and Thomas, 1977; Ziemer, 1981; Waldron et al., 1982; Endo et al., 1969). Several of these studies further show negative correlations between root shear strength and soil loss due to mass slippage.

Stocking and Elwell (1976) state from their years of experience that they believe roots bind soil aggregates. Many researchers have found that roots often increase aggregate stability. During World War II, new grasslands were frequently cultivated in England. Low (1955) noted higher yields and strikingly improved soil structure over old cultivated fields. After some study, he suggested that the decay of grass roots into organic matter increased the aggregate stability. Many researchers believed that polysaccharides and related organic substances occurred as a mucilage on roots which bound them to soil particles (Greenland et al., 1962; Oades, 1978; Tisdall and Oades, 1979; Reid and Goss, 1980; Monroe et al., 1987). However, Reid and Goss (1981) pointed out that the data are not consistent. Most of these studies based their conclusions on dry aggregate stability measurements, but when repeated using wet aggregate stability, the pattern was not necessarily the same. While ryegrass and rotations of alfalfa were found to increase aggregate stability, studies with maize and wheat demonstrated no consistent tendency to do the same (Tisdall and Oades, 1979; Goss and Reid, 1979; Reid and Goss, 1980; Page and Willard, 1946). The mucilage on the root surfaces was believed to be excreted by the root or bacteria and contained glucan, glucouronides, and polysaccharides, facilitating the binding of roots to soil particles (Foster and Rovira, 1976; Goss and Reid, 1979). In greenhouse pot experiments, Tisdall and Oades (1979) found that vesicular-arbuscular mycorrhizal hyphal length on rye grass roots correlated much better with aggregate stability than did root length of the rye grass. They concluded that not the roots themselves but root or bacterial exudates and also hyphae on the roots are the cause of root binding to soil particles, increasing soil aggregation.

Elwell and Stocking vigorously emphasize the effect on soil loss of live plant cover. Surface cover alone has been shown in numerous studies to drastically reduce soil loss but the lack of situations in which surface cover is removed and roots are left undisturbed are seldom. Most studies examine the effect of vegetative cover or mulch on soil loss without explicitly distinguishing between the effect of surface cover versus the effect of roots in the soil. For example, Hudson (1957) showed that 2 sheets of mosquito gauze placed 15 cm above a bare sandy-clay loam soil surface sharply reduced erosion and runoff to nearly the same level as did a complete grass treatment when compared to an exposed bare treatment. Hudson concluded that the effect of a root mat on slowing runoff flow or stabilizing good soil structure was secondary to that of surface cover, although there was no separate treatment investigating only the effect of roots. In fact, soil loss increased from 0 to 4.5 T/ha per cropping season under the gauze but dropped from 6.5 to 0.2 T/ha per cropping season for the grass treatment over a period of 3-4 years. If it were assumed that the grass surface cover was 100 percent for the entire period (Hudson does not include this information), this would suggest that the roots may be an important factor also. Another problem is that many studies suppose various C factor effects to be additive. In Hudson's experiment, it is theoretically possible that the roots and surface cover separately could equally limit soil loss, but inclusion of the other component would have little added effect.

One of the few situations where the effect of roots can be studied are on sites where the vegetation has been burnt. It is already well known that soil losses in undisturbed tropical forests tend to be extremely small. But it has been demonstrated that soil loss varies widely upon clearing and is very dependent on the method of clearing. When the soil is bulldozed or cleared by hand and immediately tilled, soil loss tends to increase sharply. Studies examining the effects of cut and burned vegetation on soil loss show mixed results. Soil loss upon clearing by this method is of some interests here because above-ground vegetation and most surface cover has been removed, but roots in the soil still exists in the soil and do not deteriorate immediately.

Trouse (1979) observed infiltration rates in a rainforest to be 50 cm/hr but dropped to 1 cm/hr after bulldozing and cultivation. Seubert et al. (1977) found clearing a rainforest in the Amazon jungle by bulldozing compacted the soil and sharply reduced cumulative infiltration rates compared to clearing by slash and burn. The rates were respectively 0.9 and 12 cm/hr. Carlos (1985) also compared clearing by bulldozing to slash and burn. He found that for the 0-5 cm depth, bulk density and macroporosity was 1.31 g/cc and 4.1% for the bulldozed plots and 0.84 g/cc and 18% for the burned plots. Infiltration for the burned plots was 4.5 times that of the bulldozed plots. Lal et al. (1979) also found clearing by bulldozing as compared to slash and burn increased bulk density, decreased infiltration, and increased resistance of the soil although statistical test of the data was either weak or unavailable.

Nye and Greenland (1964) argued that soil losses were low during the first season on slashed and burned fields because the soil maintained its constitution. Which soil characteristics are maintained were not specified. They note that Gongrijp (1941) found on a slashed and burned site in West Java that soil loss was 5.3 T/ha/yr the first year but increased to 50 T/ha/yr the following year. Lal (1977), Ofori (1974), and Watters (1971) claim soil loss on swidden fields in Latin American and Africa are low if they are cultivated for a only short period. Hatch (1982) provides data for a swidden field in Sarawak, Indonesia where no increase in soil loss occurred during the 1st year of cropping. Kellman (1969) found soil loss on a Mindanao swidden field in the Philippines to be 0.7-1.4 T/ha/yr during the 1st year of cultivation but to be 5.5 and 54 T/ha/yr for 2 and 12 year old swidden fields respectively. Mensah-Bonsu et Obeng (1979) also measured soil loss on a recently cleared site in Ghana to be low but increased by a factor of 10 the 2nd year of cultivation and even more the 3rd year.

In other slash and burn cases, the trend is opposite. Mishra and Ramakrishnan (1983) measured sediment loss to be very high (50 T/ha/yr) during the 1st year of cultivation after clearing on an Indian highland site, though it is not clear how the site was tilled. Kyuma and Pairintra (1983) found soil loss for the first year of cultivation to be high on 2 upland sites in shifting cultivation in Northeast Thailand (70-86 T/ha).

The great variation in the manner of slash and burn cultivation practices and the complicating factor of adding ash to the soil surface, which may contribute to sealing the surface, make it difficult to generalize about how root residue might affect subsequent soil losses, but it appears that it is very plausible that roots that have not been disturbed or removed from the soil after clearing continue to stabilize the soil structure for at least a short period of time.

Root content on our plots is relatively very high, even after bulldozing (Chapter 5). Gower (1987) measured live roots 0-5 mm in diameter in a Costa Rican tropical lowland rainforest with 3800 mm/yr rainfall and found root biomass to be 6.6 T/ha to 50 cm depth. Roots less than 1 mm in the 0-5 and 5-40 cm depths were found to have a biomass of 0.23 and 0.31 T/ha respectively.

2. Surface Cover

Surface cover has been repeatedly shown to be very effective in reducing soil loss even in small amounts (Hudson, 1957; Meyer and Mannering, 1971; Elwell and Stocking, 1976; etc). The surface soil structure is protected from being broken down by raindrops. Raindrops rearranges smaller particles and redeposits them, blocking up larger pores (Lowdermilk, 1930). Duley (1939) found that if the soil surface was protected from direct raindrop impact (using straw or burlap), high infiltration rates could be maintained. When the covers were removed, infiltration rates rapidly decreased.

Research demonstrates that the relationship between surface cover and soil loss tends to be in the form of a negative exponential curve. Stocking's (1988) generalized curve roughly estimates that 5, 10, and 20 percent live vegetative cover reduces soil loss by 20, 45, and 65 percent respectively. On slopes of 15%, Meyer et al. (1970) found in simulated rainfall studies that while 95 and 71 percent surface cover of unincorporated straw mulch respectively reduced soil loss by 98 and 80 percent, only 34% cover still reduced soil loss by 68%. Norton et al. (1983) also found a negative exponential relationship between surface cover and soil loss in an experiment studying the effect of unincorporated crop stubble on soil loss. Soil loss dropped 80% with only 10% cover. Although surface cover generally tends to reduce soil loss, the effect on runoff is much less drastic. Meyer et al., (1970) for example, found 34% surface cover reduced soil loss by 68%, but that runoff was reduced by only 24%. In fact, when the soil was wetted first, runoff was not reduced at all by any amount of increased surface cover.

IV. MATERIALS AND METHODS

A. Description, Preparation, and Installation of Experiment

1. Site Description

The site of the project is located on the Hawaiian island of Kauai at the University of Hawaii Wailua Experiment Station, on the eastern windward side of the island, at an elevation of 160 m. The station has a mean annual rainfall of 2500 mm, ranging 1800-3800 mm. Annual mean, average maximum, and average minimum air temperatures are 22, 26, and 20 degrees Celsius respectively. Summer is generally somewhat drier than winter months. The site of the project encompasses an area of 140 m by 30 m and is located on a hillside with an approximate 40 percent slope.

The soil is described as a Halii series and until recently was classified as a clayey, ferritic, isothermic Typic Gibbsihumox, (Ikawa et al., 1985). The Halii soil series has since been reclassified as a very fine, sesquic, isohyperthermic Anionic Acrudox. As both classifications indicate, the Halii soil series is a highly weathered soil, and occurs in an environment where rainfall and thus humus are both high. The soil net surface charge is positive within 120 cm of the surface (Appendix II). The Halii soil series is a common soil on the experiment station, and has been subjected to laboratory analyses by the University of Hawaii. Data are given in Table 7. Effective CEC and aluminum saturation are both low. Base saturation at field pH is low. For the 0-33 cm depth, the soil is strongly acid and delta pH is slightly negative. The C horizon on the specific study site itself is saprolite, occurring at 1.3-1.6 m depth.

Table 7. Laboratory data of Halii gravelly silty clay.[a]

Depth	Horizon	Sand	Silt	Clay	BD	Organic C	Extractable Iron Fe	Extractable Iron Fe_2O_3
--cm--		-------% < 2 mm------			g/cc	-%--	------%-------	
0-33	Ap	24.5	21.8	53.7	1.40	2.87	25.8	36.9
33-58	B21	9.3	15.6	75.1	1.22	1.91	27.5	39.3
58-76	C1	27.5	28.9	43.6	1.15	1.31	26.5	37.9
76-112	C2	26.3	32.3	41.4	1.15	0.99	24.7	35.3

Depth	Extractable Bases Ca	Mg	Na	K	Sum	CEC (pH 7) NH_4OAc	Extract Al	pH H_2O	pH KCl	pH Delta
--cm--	---------------------meq/100 g soil---------------------									
0-33	3.04	.45	.15	.15	3.79	16.01	.1	4.98	4.59	-.39
33-58	1.16	.18	.12	.07	1.53	12.97	.1	5.27	5.07	-.20
58-76	0.37	.04	.06	.05	0.52	8.12	<.1	5.23	5.28	.05
76-112	0.28	.03	.07	.06	0.44	6.97	<.1	5.00	5.22	.22

[a] Taken from Ikawa et al., 1985.

Prior to clearing, the site was covered with thick brush vegetation, chiefly false staghorn fern, strawberry guava, and Melastoma malabathricum L. The guava and melastoma grew to heights of about 4-6 m and the fern ranged 1-3 m, most of it above 1.5 m.

2. Clearing and Preparation of Field

It was initially hoped to burn the site to retain most of the nutrients in the plants and topsoil, to minimize soil variability, and to simulate typical clearing practices in tropical regions. The site was in fact burned incompletely, but continuous ridges were found running diagonally down the slope (possibly from a very old pineapple field), and would have had to been levelled before the erosion plots could be installed. Otherwise, runoff water would gather along the sheet metal where it intersected these ridges, creating a concentrated and very erosive flow of runoff. Manual levelling and installation of erosion plots would also have been very difficult and expensive since all roots and stumps in the soil remained after burning.

The entire site was then cleared with a bulldozer. Because the slope was so steep, the driver bulldozed the site from the top of the hill down. The field was bulldozed to the shallowest depth possible but still remove all large roots and stumps to allow for tillage. The field was then disked twice with a bulldozer to a depth of 30-40 cm in order to break up the surface for levelling. Because of the short slope, the driver felt it would be far easier to till the site by running across the slope. The site was too steep to work with rubber-tired tractors. The disk left rills 20-40 cm deep and it was necessary to hand hoe and rake the soil surface until it was satisfactorily smoothed.

3. Plot Preparation and Description

As previously mentioned, there were 4 treatments replicated 3 times in a completely randomized design (Figure 5). In the latter alleycrop treatment, the cut loppings were spread evenly on the soil surface about the crops. When the leaves had dropped off the cuttings (at 2 weeks), the cuttings were placed parallel to the slope at the base of the hedgerows on the uphill side. The bare treatment was prepared in the same manner as all other treatments, serving as a control. All cropped treatments had the same annual crop and sequence.

Each plot was enclosed by sheet metal for erosion collection and was 16 m long by 4 m wide (Figure 6). Each plot had a border of 4 m

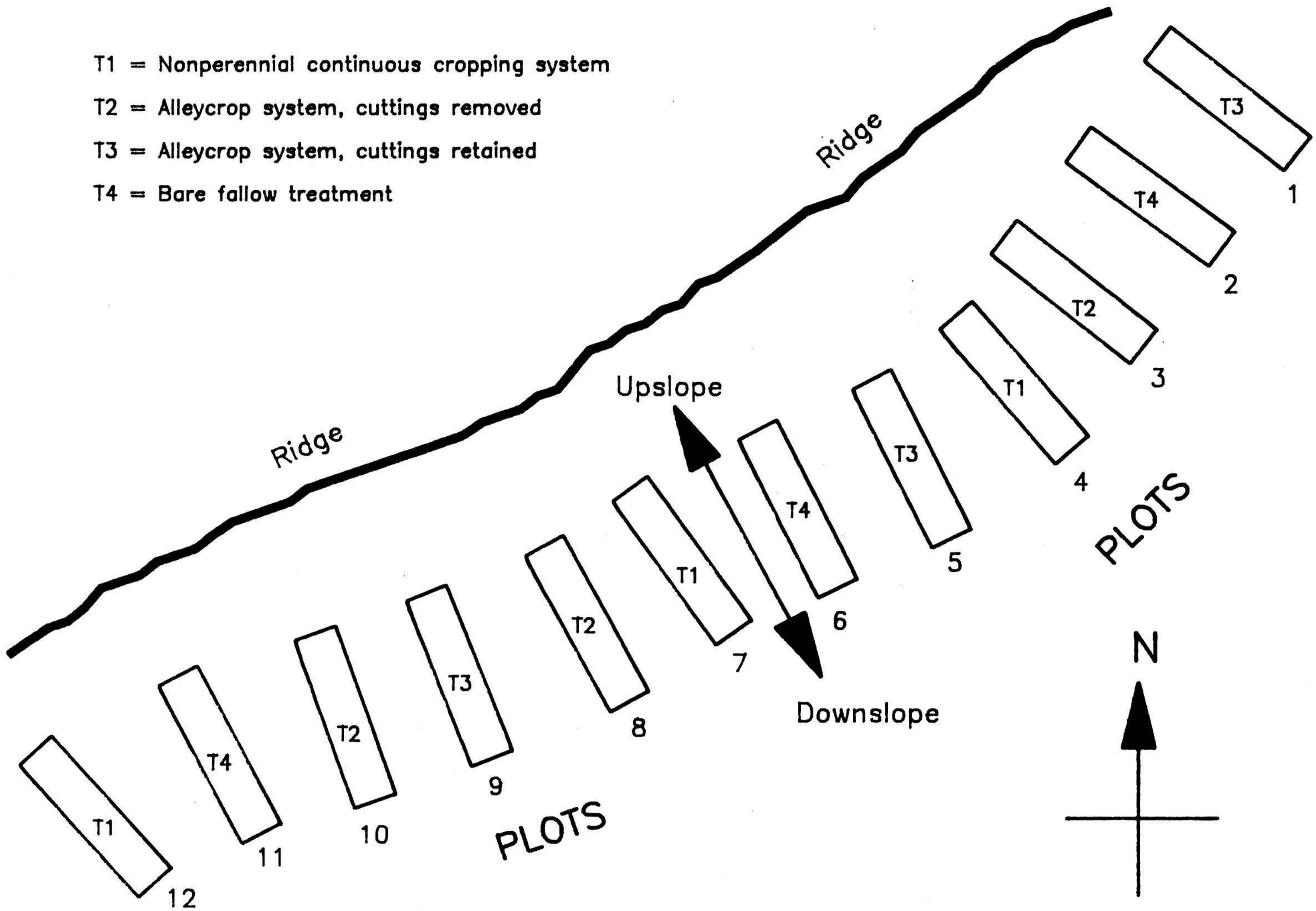


Figure 5. Diagram of plots' layout, orientation, and treatments.

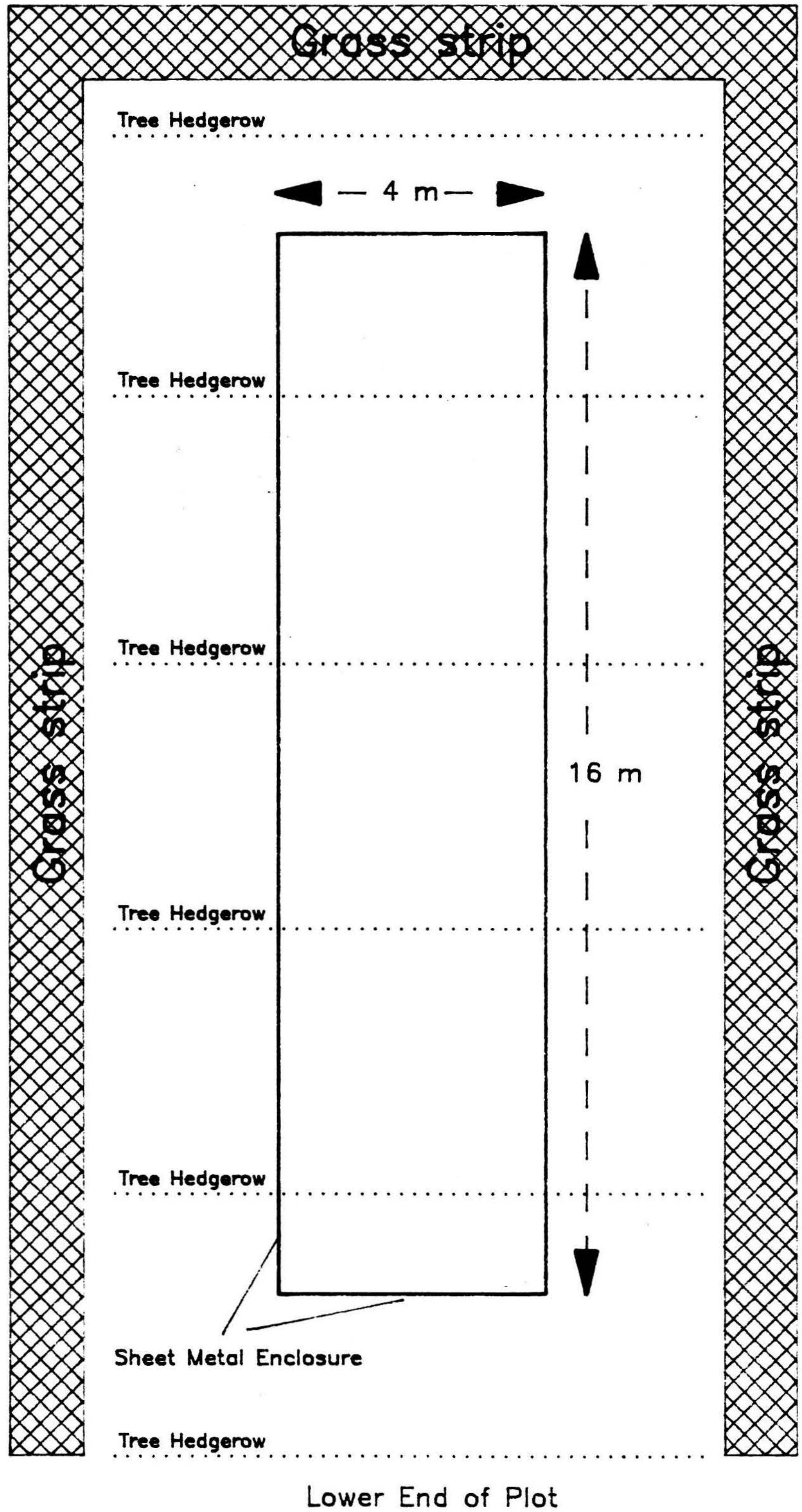


Figure 6. Diagram of a single alleycrop plot.

each at the top and bottom and approximately 2.5 m along the sides adjacent to each plot. Thus there were about 5 m separating each plot. The borders were generous in order to minimize the effects of shading and root extension of trees into neighboring plots. A grass strip about 1 m wide was established that ran along the entire top length of the site and down the slope between each plot. The purpose of this strip was to minimize sediment and runoff from entering any plot from an outside area or adjacent plot, and to provide nondestructive access by foot to the interior of the plots.

Weed control throughout the study was identical for all treatments. Weeds were severely controlled. Large weeds were pulled up and removed by hand, but small weeds, less than about 4 cm high, were sprayed with glyphosate (Round-up). Weedings took place about every 1.5-2 months. Weed growth was minimal for the first several months, presumably because the bulldozing had removed many of the weed seeds.

4. Hedge Trees

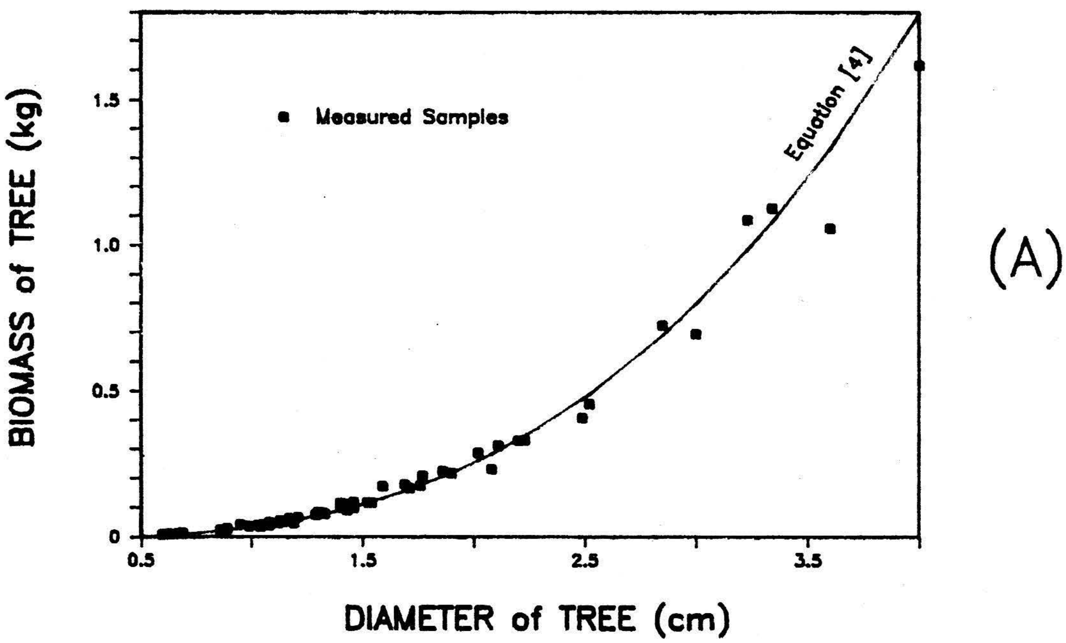
The tree species planted was Sesbania sesban cv. nubica, a fast growing nitrogen fixing perennial native to Africa. It was direct seeded and thinned to one tree per 10 cm interval within each row. Rows were 4 m apart with the annual crops planted between these rows. Thus there were 4 complete alleys within each plot (Figure 6). Benchmark steel stakes were driven into the ground at the base of two hedgerows for each alleycrop plot and replicated on all treatments at the corresponding location, to allow for measurement of any build-up of sediment and plant matter at the base of the hedgerows. The trees were planted in early August, 1988. The immediate area where the sesbania seeds were planted was fertilized with N, P, and K at a rate of 50, 100, and 100 kg/ha respectively and limed with fine calcium calcite at 0.25 T/ha. The fertilizer was buried at 10 cm depth. It was feared that the soil was so infertile that without fertilization, establishment of trees would fail. The immediate area was a strip of only 20 cm width running the entire length of each row. All plots received fertilizer.

Steps were taken in this study to minimize any terracing of the slope. El-Swaify (personal communication, 1988) has noted that many alleycrop systems he has seen were planted on pre-terraced slopes. However, while preparing a seedbed for the trees planted in the alleycrop treatments to ensure good germination, a ledge 15 cm wide was formed. This ledge was replicated on all treatments.

The trees were cut back to about 40 cm in height during the 1st week of February, 1989, or 6 months after planting, and cuttings removed or applied to the site according to treatment. Biomass of the tree cuttings were estimated using an allometric model (Table 8). Both height and stem diameter were measured from 66 sample trees from two 4 m row sections to develop the model but diameter alone was found to be an adequate parameter for predicting biomass (Figure 7A). The model is

$$B = D^{2.80} * 37.0 \qquad [4]$$

where B equals total dry biomass in grams and D equals stem diameter at cutting height in centimeters. In order to test the model, 18 1-meter sections of hedge trees (one from each row in the T2 treatment plots)



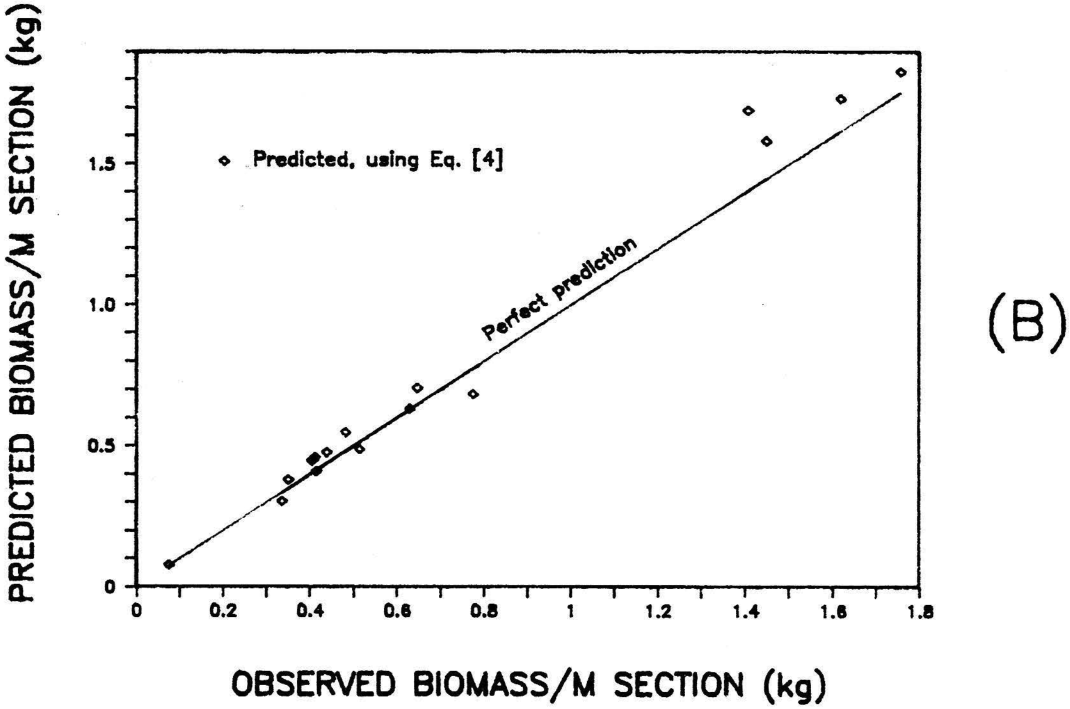


Figure 7.

(A) Derived fitted model from Sesbamia sample trees (Eq. 4).

(B) Comparison of observed and predicted biomass of 1 m sections of Sesbania hedgerow, using the model, Eq. [4].

Table 8. Dry above-ground biomass of Sesbania at time of cutting, 6 months after planting.

Plot	Loppings	Biomass (T/ha)[a]
1	Retained	1.3
3	Removed	2.0
6	Retained	1.7
8	Removed	1.5
9	Retained	2.3
10	Removed	1.3

[a]Biomass is reported as dry biomass per unit of total cropped area. Since there is one hedgerow every 4 m, if 1 m of hedgerow had a biomass of 4 kg, then biomass would be 1 kg/m² or 10 T/ha.

were cut and weighed prior to cutting back all other trees and compared to predicted estimates, using Equation 4 (Figure 7B). The model appears to somewhat over-estimate sections containing trees of larger diameter.

The trees did not regrow well. Most trees did coppice, but a small percentage died immediately. However, growth was very slow and nearly all trees had died within 1 year of cutting. Remaining trees were chlorotic. Poor regrowth was attributed to the combination of the cutting back shock and particularly the very low soil fertility. Trees bordering bare plots, which had also been fertilized after a uniformity trial, grew markedly better than other plants and were the only trees living after 1 year. Crops also grew better in this area.

5. Uniformity Trial

A uniformity trial of a hybrid maize variety (Pioneer X304C) was planted in early September, 1988, on all treatments except the bare fallow treatment. Seed was planted every 20 cm in rows 1 m apart on the contour of the slope, except in tree hedge rows. No fertilizer was applied except as that already applied in the narrow seedbed strip for the sesbania trees. Heights of plants were only 10-40 cm at 60 days. Visible signs of purple coloring, narrow leaves and stems, and generally very stunted growth indicated severe P deficiency. The crop had been so limited by P deficiency, that variation due to other nutrients and factors could not be made. There did not appear to be any pattern among plots. The lower border area of many plots had taller plants, presumably because the bulldozer had pushed some of the topsoil down from the upper slope. It appeared that plants in Plot 12 tended to be more chlorotic, but no data was taken to support this statement.

6. Cassava Crop

The maize crop was sprayed with glyphosate and later pulled up by hand and removed from the plots. Plants taller than 40 cm were cut at the base to minimize soil disturbance. A cassava crop was planted December 8, 1989 (2 months before the trees were cut back) on all cropped treatments at a 1 by 1 meter spacing. For alleycrop treatments there were 3 rows within each alley. Cassava cuttings, 25 cm in length, were planted at a slight angle to the vertical at 15 cm depth. All plots were broadcast fertilized with N, P, and K at 50, 100, and 100 kg/ha respectively, including bare plots. It should be noted that the P fertilizer would not have been incorporated. Survival of cassava cuttings exceeded 99%. It appeared there may have been a problem with a micronutrient deficiency in a few areas but this was never determined. The plants remained on the plots throughout the experimental period.

B. Soil and Runoff Collection System

Soil and runoff data was perhaps the most important data that should be taken accurately. Yet accurate measurement is not a simple task. The following extensive discussion is intended not only to describe the methods but to report in detail the difficulties of the collection equipment used here, allowing others to use the information to improve collection equipment on future erosion studies.

1. Setup and Equipment

Soil loss and runoff for each plot was quantified by enclosing a known area within each plot and collecting the runoff and eroded soil from that area. The enclosed area was 4 m wide and 16 m long with the collection equipment installed at the bottom of the plot (Figure 8). Galvanized sheet metal (26 gage) was used to enclose the measured area. A ditch was dug with picks and the metal placed vertically in the ground 5-10 cm, protruding above the surface 20-25 cm, though it is not necessary to have more than 10-15 cm of metal extending above the surface. Soil was then repacked at the base of the sheet metal to hold it in firmly. Much attempt was made to ensure that the sheet metal ran straight up and down the slope to prevent runoff from collecting and concentrating along the metal barrier. Slope length was selected at 16 m because this was the maximal length that slope was uniform. Slopes varied minimally from plot to plot (Table 1). Within each enclosed area, the surface was raked by hand to obtain a smooth uniform surface.

The collection equipment consisted of 2 troughs which funnelled runoff and soil into a container. Each trough was 2 m wide and

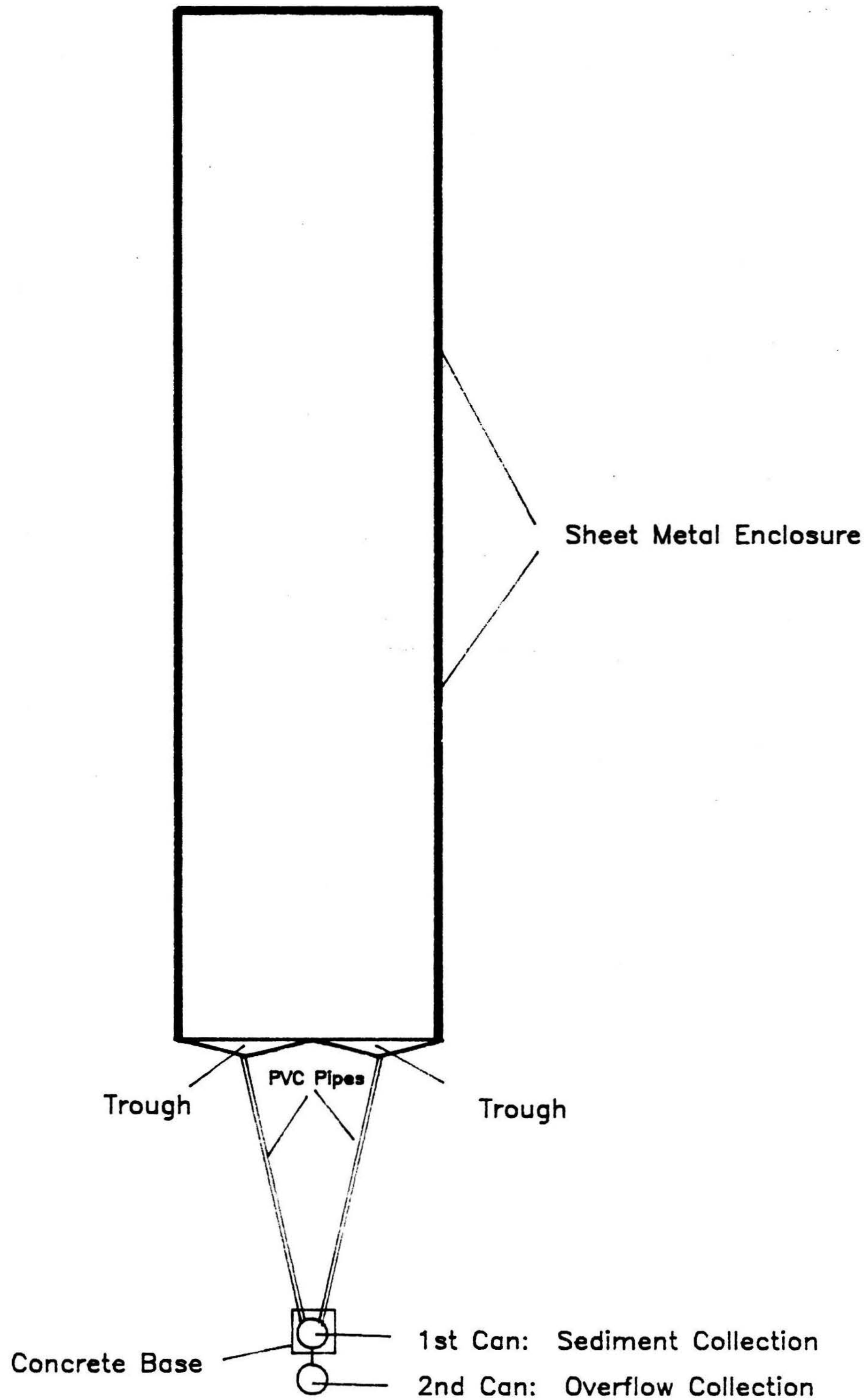


Figure 8. Diagram of sediment and runoff collection system.

installed in series at the bottom of each plot perpendicular to the slope. The troughs were made level with the slope surface of the plot so sediment and runoff moving down the slope did not drop down into the trough or have to "climb up" into the trough. Each trough had a vertical 5.1 cm (2 inches) hole in the lower end of the trough. Runoff entered here, made a 90° angle and then ran 4 m through a 3.8 cm (1.5 inches) PVC pipe into a 113 liter (30 gal) galvanized trash can. The trash can was set on a concrete slab 9 cm thick. Two 5.1 cm holes had been drilled into the side of the can, and the PVC pipes, one from each trough, were inserted.

Because of large volumes of runoff expected from the plots, a splitter system was designed such that only 1/7th of the overflow of the first can would be collected into a 2nd can (Figure 9). Each one of the first cans had 7 holes, 1.9 cm in diameter, drilled into the can's side opposite of the inlet holes, each 2.2 cm apart. These outlet holes were set just below the level of the large 5.1 cm entry holes so when runoff exceeded the capacity of the first can, it would overflow through these holes. Overflow of only one outlet, the central outlet, was collected into a 2nd galvanized trash can.

Great care was taken to ensure that the water would flow out of each outlet equally. The outlets were the exact same diameter and drilled at the same level. Each was sanded carefully to rid its edges of any burrs or unevenness. The cans were filled with water in an indoor laboratory and allowed to overflow. Overflow from the center outlet was monitored and collected. If water tended to flow out one outlet more than another, other outlets were lightly sanded until

Can #1

Can #2

Figure 9. Photograph of splitter device for runoff collection system.

outflow from the central outlet was within 5% of collecting 1/7th of total overflow. In the field, the cans were set on concrete pads to provide a stable base. Utilizing a carpenter's level, each can was shimmed with thin pieces of metal under its base until it was level. Outflow from the central hole dropped into a small trough (covered to keep out rainfall) and entered into a 2nd can. A screen was placed over the outlets on the inside of the 1st can to keep plant matter or any other matter from obstructing flow through them.

After each storm, runoff and soil loss were measured. Runoff was always measured first. Depth of liquid in both cans was measured with a meterstick and recorded. The following equation was used to obtain total volume of liquid in each can:

$$(0.0376D + 21.35)^2 * \pi * D = V \qquad [5]$$

where V equals volume of liquid in cm^3, D equals depth of the water in the can in cm, 0.0376 equals the tangent of 4.3° divided by 2, and 21.35 equals the radius of the bottom of each can in cm. Volume of any cylindrical object is equal to $\pi r^2 h$ where h is height. The trash containers used here are not perfectly cylindrical, so adjustments were made for in the above equation. Volume of liquid in the 2nd can was multiplied by 7 to obtain runoff represented by that can. Some of the liquid in the cans is not true runoff. All rainfall on the trough itself runs off into the cans. The depth of rainfall for any given storm was multiplied by the horizontal area of the troughs and subtracted from the water in the cans.

Soil loss was measured after the depths had been measured and recorded. The water was emptied out and the sediment collected. This soil was weighed wet and a sample taken to determine moisture content. If there was a large amount of sediment in the can, volume was instead estimated in the same manner as runoff and a bulk density sample was taken to calculate the mass. Runoff in both cans was stirred vigorously and a 1 liter sample also taken. This was later discontinued because the suspended soil was found to be insignificant.

2. Reliability of Runoff and Soil Loss Data

I believe accurate collection and measurement of sediment and runoff to probably be a serious problem in many erosion studies. It is unfortunate that most erosion studies do not report or comment on the accuracy of the collection equipment, especially when a splitter system is involved. The most accurate method of course would be to collect all runoff and sediment. However, because variability in surface erosion for a small area is high, plots must be large and runoff from large plots can be enormous. For example, if runoff for a 10 cm storm was only 15% for a standard unit plot of 22 by 4 m, nearly 1300 liters would need to be collected. Both storms and runoff are often much higher.

To economize, splitter systems are often devised. Many splitter systems collect a fraction of the runoff as it leaves the trough area. The assumption is that not only is the fraction collected representative but that fraction is always the same for each storm, assumptions that are both subject to considerable error. The collection system in this study was designed to minimize error in sediment collection because this was a more important parameter than runoff. The splitter system was installed after an initial collection container. The objective was to retain most of the sediment in this can so error in splitting would be limited primarily to runoff. For this particular study and soil, the design was found to be very effective in determining an accurate measure of sediment loss. Because this soil is well aggregated, nearly all sediment settled in the first can. Only once for all storms was sediment found deposited in the bottom of the second can.

As expected, the accuracy of runoff determinations was less reliable. The first obvious problem was that runoff overflowed the 2nd can for 2 storm events on Plot 12 and for 1 storm event on Plot 11, underestimating runoff. Although the collection system proved adequate for most storms, it is the largest storms when it proved inadequate and it is during these storms that the largest percentage of the year's total runoff occurs, thus introducing potentially very large error in the final runoff data.

Another problem was that there was no absolute way of knowing how accurate the splitter system is since total runoff for any storm was never collected and compared to the fraction in the 2nd can. The viability of the splitter system was suspect when the cans were calibrated in the laboratory. It was found that if a can was even slightly unlevel, outflow from the center hole varied markedly from 1/7th. Small burrs of metal around the edge of an outlet were also found to cause large error because a meniscus would be formed in front of an outlet completely halting outflow through that outlet. In the laboratory, water was clean and without foreign matter. In an actual storm, large amounts of plant and foreign matter are found in the runoff. Even an insect's wing could causes a meniscus to form in front of an outlet. When runoff is slow, error increases because the likelihood of meniscuses forming increases.

Because there was doubt about the reliability of using the adjustment fractions calculated in the lab, the splitter systems for Plots 11 and 12 (the only 2 plots with runoff) were recalibrated in the field. Calibration involved pouring known amounts of water into the troughs at various flow rates when the 1st can was full and measuring the oerflow into the 2nd can. Flow rates were chosen which were estimated to be representative of flow rates expected during a storm. The data was scatter plotted to determine if there was any relationship between the fraction collected and flow rates (Figure 10). There did appear to be a pattern. The fraction collected and error increased as flow rate increased. This was opposite of what was expected. However, the error was easily explained. As water from the troughs enters the 1st can, it splashes into the water creating small waves. Because the central outlet is directly across from the inlet holes, the waves reaching that hole are stronger and higher than those reaching other holes. Therefore, as the inflow rate increases, the disturbance increases, and a larger fraction exits via the central outlet. The original design of the inlet included a flexible tube attached to the inlet PVC pipes and extended under the surface of the water, thus minimizing disturbance of the water surface. These were later discarded because during one storm event sediment completely filled the 1st can and the tube became clotted.

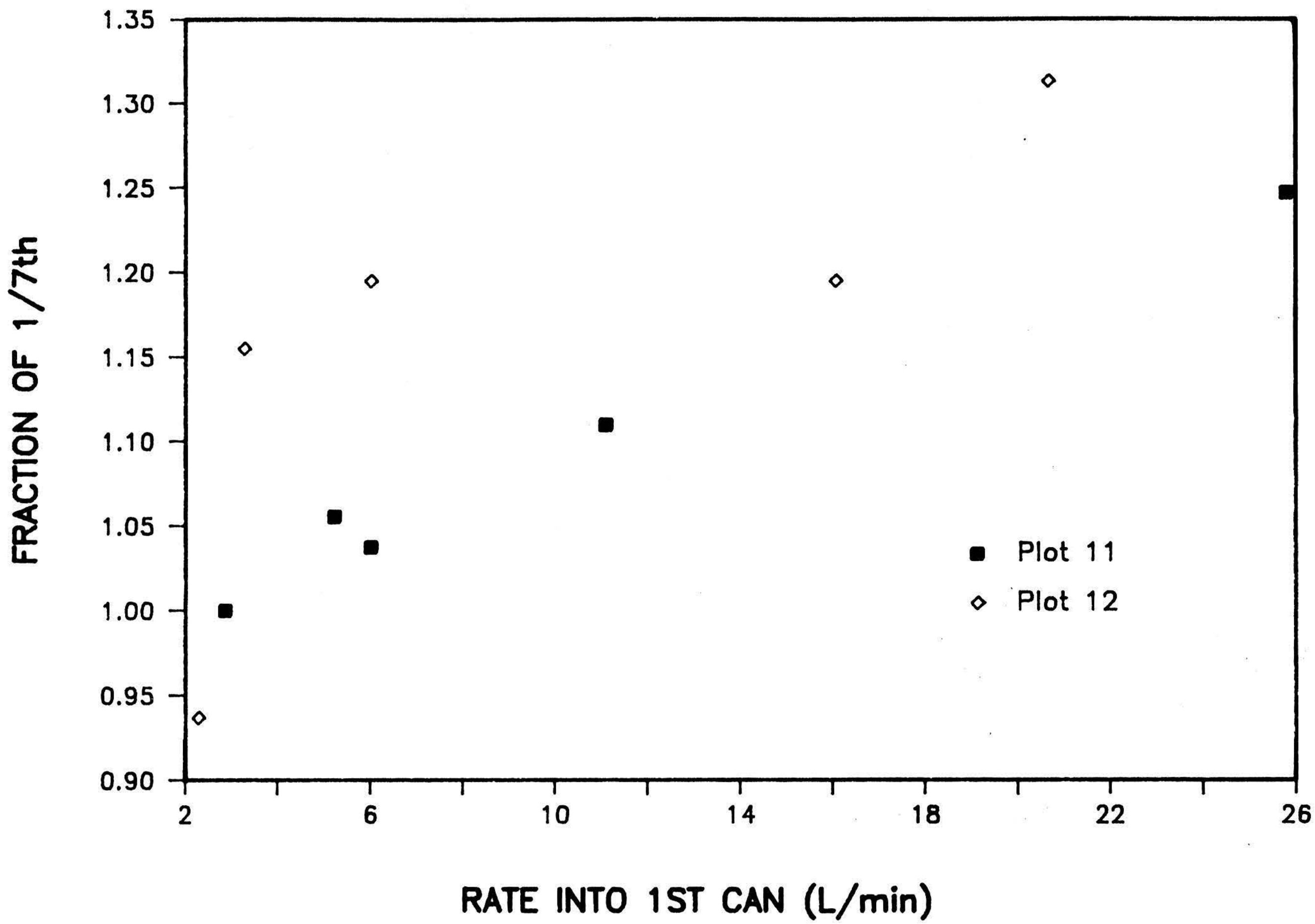


Figure 10. Fraction of expected 1/7th central hole outflow from splitter device during trial runs in the field.

An average value was computed from the calibration data presented in Figure 10 and the reciprocal of this value was taken as the adjustment factor. This factor was multiplied by 7 and by the volume in the 2nd can to obtain runoff represented by the 2nd can (Table 9). The range of error using maximum and minimum values from the calibration data was ± 20 percent. Again, error is not really known because the actual runoff from each plot was not measured.

Table 9. Adjustment factors for 2nd can, taken from field calibrations.

Plot	Fraction of 1/7th	Adjustment Factor
11	1.04	0.96
12	1.16	0.86

For purposes of this study, the sediment and runoff collection system has generally been fairly reliable. Several areas of error were eliminated or minimized. By installing the splitter system after the first can, sediment loss determinations were known to be very accurate. The concrete base served well to keep the 1st cans level and stable. They were checked from time to time and only 2 of the 12 cans had to be adjusted once each during the period of one year. Screens inside the 1st can appeared to shield most or all matter and debris from blocking the outlets. Yet, if only one foreign particle blocked the center hole, then runoff results would be extremely distorted. To eliminate overflow from the 2nd can, either a larger container is needed or a smaller fraction of the overflow from the 1st can must be collected. For studies in which runoff is very important or where a researcher intends to measure nutrient losses in sediment, this system is much less reliable. This would be particularly true for other soils, because the soil in this study aggregates unusually well and settles quickly.

It is recommended that the sheet metal barrier around the enclosed area be inserted at least 10-15 cm. Using PVC pipe is not recommended, unless the pipes are large in diameter and sharp bends are excluded. The PVC elbow was susceptible to being clogged by plant matter. A second problem was that animals, toads in our case, reside in the pipe and are another source of blockage. It is recommended that the passage from the trough to the containers be large and straight with as few points of constriction as possible.

C. <u>Determination of Rainfall and Erosivity Index (EI30)</u>

A Campbell Scientific electronic datalogger equipped with a tipping bucket raingage was used to measure rainfall. The datalogger was located between Plot 4 and Plot 5. Rainfall was recorded in 30 minute intervals. Data was recorded from the datalogger on to a cassette tape and then transcribed through a Campbell Scientific C-20 Computer Interface into a microcomputer. Six Tru-test wedge shaped plastic raingages were also installed on the experimental site, one placed between every other plot, as a check of the datalogger and backup in case of datalogger failure. The plastic raingages also served as a check on rainfall spatial variation. They were monitored daily or after a rainfall event. Erosivity was estimated as the EI30 index, developed and described by Wischmeier and Smith (1978). The EI30 index was computed as follows:

1. Calculate intensity of each 30 minute period of a storm as cm/hr by multiplying by 2.

2. Calculate the kinetic energy per cm of rainfall from intensity with the following empirical formula:

$$KE/cm = (\text{Log}_{10} \text{ of Intensity}) * 89 + 210 \qquad [6]$$

3. Calculate the kinetic energy for each 30 minute increment of rainfall by multiplying kinetic energy/cm by the increment of rainfall for that 30 minute period.

4. Calculate total kinetic energy of the storm by summing kinetic energy for all increments.

5. Calculate EI30 index for the storm by multiplying storm kinetic energy by the maximum 30 minute rainfall intensity and then dividing by 100. See Appendix I for conversion to English units.

A storm has been defined by Wischmeier and Smith as any rainfall event in which more than 1.3 cm (0.5 inch) of rain falls within a period of 6 h and is separated from other rainfall events by 6 h or more. He also includes rainfall events of less than 1.3 cm if at least 0.64 cm (0.25 inch) fell in 15 min. These events were not recorded because early measurements indicated that these rainfall events did not cause runoff nor significantly changed total EI30 values.

1. Error Between Electronic Datalogger and Recording Chart:

It should be noted that EI30 indexes computed from this electronic datalogger will tend to be a little lower than those computed with a recording raingage chart (on a revolving drum), the type of instrument from which Wischmeier and Smith most often obtained their data. This is because the datalogger records values digitally exactly every 30 min. A recording chart records rainfall continuously on a chart, making it possible to identify more accurate higher maximum intensities. For example, if 2 cm of rain fell at a constant rate between 2:45 and 3:15 and none before or after those time periods, an electronic datalogger will record 1 cm of rain for each of the periods: 2:30-3:00 and 3:00-3:30. Maximum 30-minute intensity will then be taken as 2 cm/h for the entire rain event. With a chart from a revolving recording raingage, the maximum intensity can be identified accurately as 4 cm/h (Table 10).

Table 10. Example of EI30 Index Computed by Two Different Instruments: 1. revolving drum chart; 2. electronic datalogger.

	Period	30-minute Rainfall	Intensity (cm/hr)	Energy/ cm	Energy/ Increment
1	2:45-3:15	2.0 cm	4.0	264	527
2	2:30-3:00	1.0 cm	2.0	237	237
	3:00-3:30	1.0 cm	2.0	237	237
					474

EI30 Index:

1. Drum Chart EI30: Total = 527 * .01 * 4.0 cm/hr = 21.1
2. Datalogger EI30: Total = 474 * .01 * 2.0 cm/hr = 9.5

2. Adjustment for Tipping Bucket Error

The tipping bucket raingage tends to underestimate rainfall during a high intensity period because as the bucket tips, some of the water which is coming from the funnel in a constant trickle will be lost before it can be caught by the tipping bucket. When rainfall recorded with the tipping bucket raingage was compared to the plastic raingage data, there were a few discrepancies for certain storms. It appeared there was a pattern to these discrepancies, so an estimate of the error was sought and compensated for as explained below.

For the major portion of rainfall, readings were essentially identical. However, datalogger readings during heavier rainstorms were often 5-22% lower than the that of the plastic raingages. A comparison of rainstorms of which data was available from both instruments showed that in every case in which there was at least one 30 min period in which the intensity was greater than 2.5 cm/h, the mean of the Tru-test raingage readings was at least 5% greater than datalogger readings. In every rainstorm in which intensity for every single 30 min period did not exceed 2.5 cm/h, readings of both instruments were within 4% of each other, the error averaging 0%. It was probable that the underestimate of true rainfall by the tipping bucket raingage could be attributed to only those 30 min periods. Because the EI30 index is the direct product of a storm's total kinetic energy and the maximum intensity, a storm's EI30 value could be significantly underestimated.

For example, a rainfall event occurred 1/13/89. The datalogger recorded 0.48 cm less than the Tru-test raingage, an error of only 11%. But if we assume all this occurred during a single 30 min period (there was only one period when intensity exceeded 2.5 cm/h), the real value for that increment of rainfall would be 1.73 cm instead of the recorded 1.25 cm and the adjusted EI30 index for the storm would actually be 60% higher. Therefore, for storms in which at least one 30 min period exceeded an intensity of 2.5 cm/h, the difference between Tru-test readings and datalogger readings were added to that 30 min increment. The EI30 index values were then computed again. For storms which had more than one 30 min period with intensities exceeding 2.5 cm/h, those increments were adjusted on a weighted basis. For 3 storms, corresponding Tru-test raingage readings were unavailable. Those increments for which intensities were greater than 2.5 cm/h were adjusted by Equation [7]. This equation was derived from a logarithmic regression from lab calibration data of the tipping bucket raingage. R^2 for the linearalized logarithmic regression was .999.

$$\text{true rate} = \text{recorded rate}^{1.13} * .973 \qquad [7]$$

$$df = 4$$

3. Missing Data

Data was accidentally not recorded from the datalogger on several occasions. Daily total rainfall had been recorded during these occasions with the Tru-test raingage. In order to estimate the EI30 index for missing data, available data of total rainfall for a storm was plotted against the corresponding EI30 index to determine a regression equation. There appeared to be two patterns contained in the regression, so a differentiation was made between data for storms in which there had been soil loss and those which there had not (Figure 11A & 11B). Two separate regression equations were calculated. Equation [8] was the derived linear equation for storms for which soil loss had occurred and Equation [9] was the derived polynomial equation for storms for which soil loss had not occurred. R is equal to rainfall (cm).

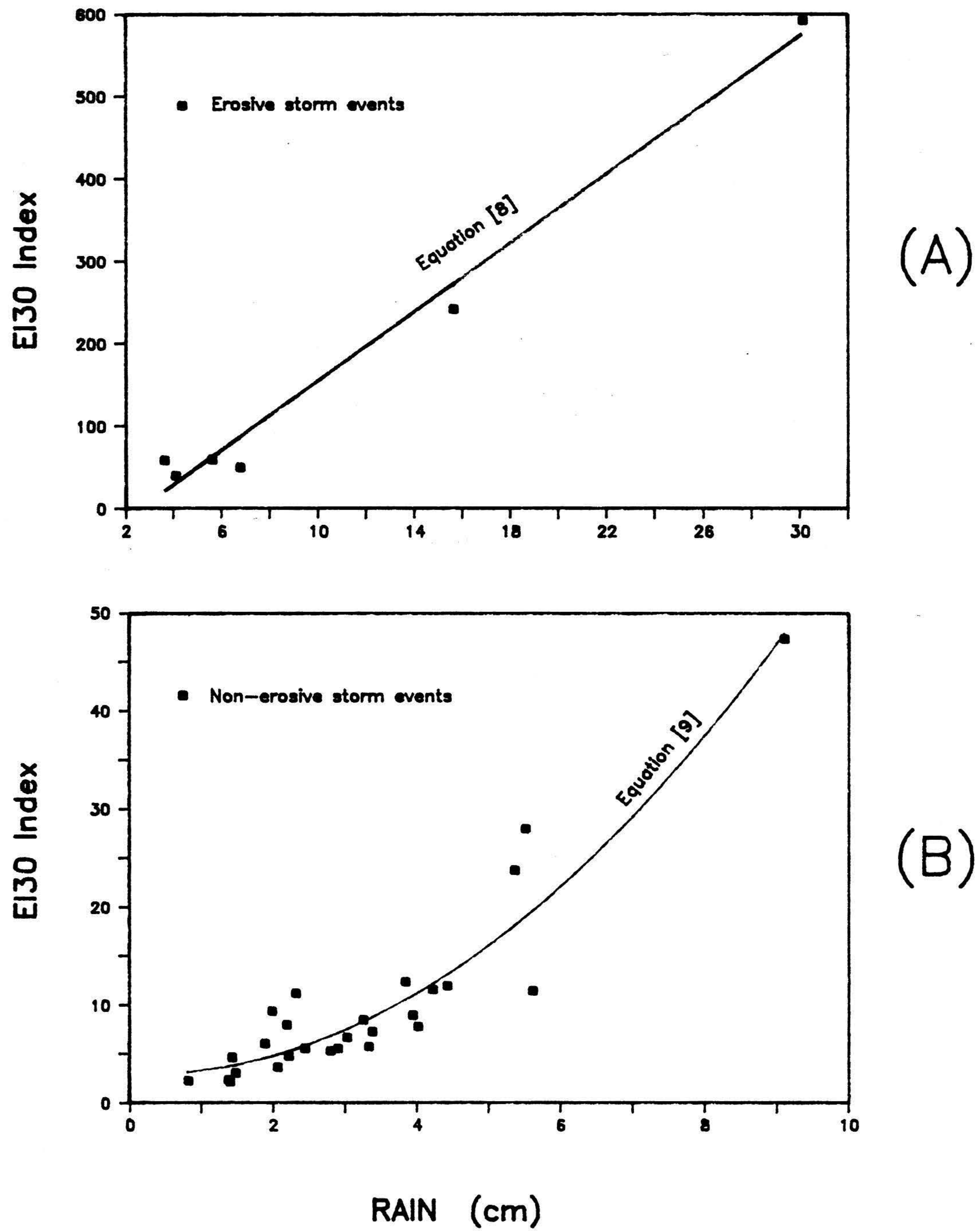


Figure 11. Scatter plot of rainfall/storm vs EI30/storm for (A) erosive storms and (B) non-erosive storms from Plot 12, and derived models used to estimate missing EI30 data.

$$EI30 = R * 20.9 - 54.8 \quad [8]$$
$$r^2 = .983,\ df = 4,$$

$$EI30 = 3.01 - .185\ R + .563\ R^2 \quad [9]$$
$$r^2 = .88,\ df = 24,$$

D. Chemical Properties

1. Determination of Soil pH

Soil pH was determined by prescribed methods of McLean (1965). Samples were air-dried for 2 days in an air-conditioned room. Five grams of dry soil mixed with 5 ml of deionized water or 1.0 M KCl.

From each plot, 6 samples were taken at the 0-5 cm depth, and 3 from the 5-40 cm depth. The samples were taken from locations selected in a systematically randomized fashion as marked in Figure 12 (p. 72). Samples were taken just outside the enclosed section of the plots to minimize disturbance to the plots.

2. Determination of Soil Organic Carbon, Event 1

A data event of sampling henceforth refers to a specific separate data set. A one gram sample was ground to a fine powder with a mortar and pestle and then analyzed in an organic carbon analyzer. Organic carbon samples were the same as used for the pH analyses.

3. Determination of Soil Organic Carbon, Event 2

Samples were prepared and analyzed as in the 1st event. Samples were taken from only Plots 10-12 locations (marked in Figure 13, p. 73), which are the same as the profile pits which are described later. Samples were taken from the A horizon and from the top 10 cm of the B horizon. A weighted value for the 0-40 cm depth was also calculated.

4. Mineralogy Analyses

Six subsamples each were taken at 0-10 cm depth from Plots 10, 11, and 12 as marked in Figure 12, and pooled into 1 sample for each plot. Two duplicates from each sample were analyzed by X-ray diffraction. The samples were first treated with hydrogen peroxide to oxidize organic matter. Samples were ground in a mortar and pestle and sieved through a 45 μm sieve. The sieved portion was centrifuged at 1000 rpm for 3 minutes. The soil in suspension was dried and analyzed. For Plots 11-12, it was necessary to bring samples to a pH of 8.0 with 1.25 M NaOH before centrifuging to keep an adequate amount of soil in suspension.

E. Soil Physical Properties

1. Determination of Bulk Density, Event 1

Brass cylinders (9.8 cm in diameter and 7.6 cm in depth) were pushed and driven with a hammer into the ground. Soil was excavated around the cylinders so they could be easily removed. Soil was then cut underneath the cylinder flush with the bottom of the cylinder. The samples were immediately weighed, and then oven-dried at 105° C and weighed again. Both dry and wet (soil plus water at time of sampling) bulk density (BD) were calculated. Soil samples were taken at two depths, 0-10 and 10-20 cm. The samples were collected less than 6 h after occurrence of the first storm causing soil loss in Plots 11 and 12

(11/6/88). Three, 2, and 1 sample locations were respectively selected from Plots 12, Plot 11, and Plots 1-10 as marked in Figure 12. It seemed important to collect samples quickly as the differences in moisture between plots would be minimized if the soil was allowed too much time to dry. To protect against false readings in moisture between Plots 11 and 12 versus Plots 1-10, the order of collection began with Plot 12 and proceeded towards Plot 1, taking only one sample per plot. The 3 remaining samples from Plots 11 and 12 were then taken.

Effective macroporosity (EM) was defined and estimated as the volume of soil which was occupied by air at time of sampling, or total porosity minus volumetric moisture content. Total porosity, p, was calculated as

$$p = 100 - (BD/PD) * 100 \qquad [10]$$

where BD is equal to oven-dry bulk density and PD is equal to particle density. Particle density was taken as 3.0 g/cc for all plots.

2. Determination of Bulk Density, Event 2

A 2nd set of BD samples was taken. Wet and dry BD, and EM were determined as before. Six samples each were taken from Plots 10, 11, and 12 at the 10-20 cm depth only. Locations are marked in Figure 12. Locations were selected in a systematic randomized fashion. Particle density was not assumed to be 3.0 g/cc for each plot, but determined for each plot as described in a following section.

3. <u>Determination of Bulk Density, Event 3</u>

Four more samples were taken from Plot 12. Four were also taken just outside of Plot 12 at locations where the bulldozer had removed the topsoil but had not disked. An additional 4 samples were taken nearby where the site had been burned but there had been no bulldozing activity. Locations are marked in Figure 13. All samples were taken from the 10-20 cm depth. The samples were subjected to the same analyses as the 2 previous bulk density events.

4. <u>Determination of Particle Density</u>

Particle density was determined by the pycnometer method described by Blake (1965). Samples were the same as the Event #2 BD samples but parallel samples were pooled to comprise 3 samples only from each plot.

5. <u>Determination of Aggregate Size Distribution, Event 1</u>

Six soil samples each were taken from the surface of Plots 10, 11, and 12 at 0-10 cm depth. Sample locations were selected in a systematically randomized fashion and are marked in Figure 12. Size distribution of aggregates was determined by the wet-sieve method using the Yoder (1936) type sieve machine developed by Tiulin (1928) and later modified by Yoder, as described by Kemper and Chepil (1965). Soil samples were air-dried in an air-conditioned room for one day and pre-sieved through a 4.75 mm sieve. The samples were wet sieved for 30 min at 30 cycles per minute through 5 sieves with mesh sizes equivalent to 2.00, 0.85, 0.425, 0.25, and 0.10 mm. Oven-dry weight was determined for each size class.

Three wetting methods of the samples were tested. They were wetting with a fine spray, wetting by capillary action, and direct immersion. There was no significant differences among means or variation between the 3 methods. Therefore, the simplest method, direct immersion was used with the true field samples.

6. Determination of Aggregate Size Distribution, Event 2

The methods were identical as for Event #1. The samples were taken at the same locations as the 1st event. However, these samples were taken at the 0-0.5 cm depth.

7. Soil Profile Descriptions

Two pits 1.5 m deep and three pits that extended only into the B horizon were dug and their profile described by a Soil Conservation Service scientist. Their locations are marked in Figure 5.

F. Vegetal Properties

1. Determination of Soil Surface Cover

Soil surface cover, both by plant residue and rock, was estimated for each plot on 1/10/89 before cassava was well-established. Ten sample locations were selected in a systematic randomized fashion as marked in Figure 12. The sample locations are not evenly distributed across each plot. The density of sample locations is slightly less at the top of each plot and much denser at the very bottom portion of the plot. Locations were purposely selected in this way because it visually appeared that while variation in surface cover at the top of the plots tended to decrease, it appeared to be very high at the bottom. Bulldozing, tillage, and hoeing caused rocks and litter to be moved down the slope increasing not only the amount of cover at the bottom of the slope but also increasing surface cover variation. The 3 samples at the bottom of the plot were averaged as one datum for statistical analysis.

A color slide was taken at each sample location. Pictures were taken from a 35 mm camera at shoulder height (1.5 m) perpendicular to the surface. The area of each sample site was about 0.5 m^2. Each slide was viewed through a projector against a dot matrix grid. Percentage of dots on the grid intersecting with rock and plant residue were counted and recorded separately and equated with percentage surface cover.

One disadvantage of this method is the high cost of film and development. Stocking (1988) describes a technique which uses the same process but instead cover is estimated directly in the field. The technique described involves viewing the surface through a simple instrument which has a number of evenly spaced set of double holes which serve as sights similar to a gun sight. The user simply looks through each sight and determines if cover is present or not at the sighted location. The instrument is mounted on a portable stand at eye level and can be easily moved about. An important advantage would be that the user would be better able to relate actual surface percent cover in the field to numerical values since cover is determined immediately.

2. <u>Determination of Fine Root Content in Soil</u>

Fine root content is selectively defined. Fine roots refer only to false staghorn fern roots of any length less than 1 mm in diameter which were nonliving. The objective was to determine fine roots in the soil that were residue from the site's previous vegetation. Thus, all new and live roots from cassava, maize, sesbania, and weeds were purposely excluded. The fern roots were easy to identify, tending to be hard, somewhat brittle, of the same diameter, and branched. At least 95% of all fine roots were dead roots of the false staghorn fern.

Approximately 100 g dry weight soil was collected for each sample and the soil laid out on newspaper to air-dry. Rocks in excess of 1 cm in diameter were removed from the sample. Soil was lightly broken down with fingers while still moist. After drying, each sample was then thoroughly mixed and a subsample of approximately 25-90 g was taken and weighed, depending on apparent root content. Moisture content was also determined. The first subsample was sieved through a 0.8 mm screen. Only that soil retained by the sieve (about 90%) was kept. This portion was placed in a cup and flooded with water. All matter that floated was poured off into a 0.25 mm sieve and strained. This process was repeated 2-4 times until all visible plant matter was removed from the sample. The plant matter was oven-dried and then placed on a tray and fern roots were separated with tweezers from seeds, leaves, bark, other roots, and small soil particles. Only the fern roots were retained and weighed. These fine roots ranged from 1 mm to 80 mm in length and less than 1 mm in diameter. The vast majority were about 0.15-0.70 mm in diameter.

In order to determine the degree of error of this technique, two soil samples with very different root content were taken. Each sample was thoroughly mixed and divided into 4 equal parts, and fine root content determined for each subsample (Table 11).

All samples were systematically randomly collected. Samples were collected in 5 separate events. In the 1st event, samples were taken from 3 locations of each plot, located as marked in Figure 12 at the 0-5 cm depth. In the 2nd event, 6 additional samples each were taken from Plots 2, 3, 11, and 12 at 0-5 cm depth as marked in Figure 12. In the 3rd event, samples were only collected from Plots 11 and 12 and the border area between these plots at locations marked in Figure 13. Samples for this event were also taken from the 0-5 cm depth of soil. In the 4th event, samples were taken at the same location of pits as marked in Figure 13. These samples were taken from the entire A horizon, a depth to about 20-40 cm. Values were adjusted so they could be reported as average fine root content in the 5-40 cm depth. In the 5th event, samples were taken from Plots 2 and 3 at the 5-40 cm depth (sample locations marked in Figure 12).

Table 11. Test of precision and error in soil fine root content (g/kg soil) determination technique.

Subsample	Plot 10	Plot 12
1	15.0	1.06
2	14.5	1.22
3	14.8	1.02
4	16.4	1.26
Mean:	15.2	1.14

Coefficient of Variation = 0.92%.

3. Determination of Large Roots

Large roots defined in this category were those roots 1 to 5 mm in diameter of any length and derived from vegetation existing on the site before clearing. The large majority of the roots were between 2-4 mm in diameter. These roots were also essentially composed of nonliving false staghorn fern roots. All cassava and live roots were excluded. Any roots larger than 5 mm were also excluded, of which their were very few.

Only Plots 10, 11, and 12 were sampled. Three sample locations were selected in a systematically randomized fashion. Their locations are marked in Figure 12. Each sample location consisted of an area 60 by 60 cm. The soil from each sample area was removed to a depth of 10 cm and sifted in the field through a 6.3 mm sieve. Some roots did pass through the sieve but could easily be handpicked out from the soil that had passed through the sieve. The roots were rinsed of soil, oven-dried, and then weighed.

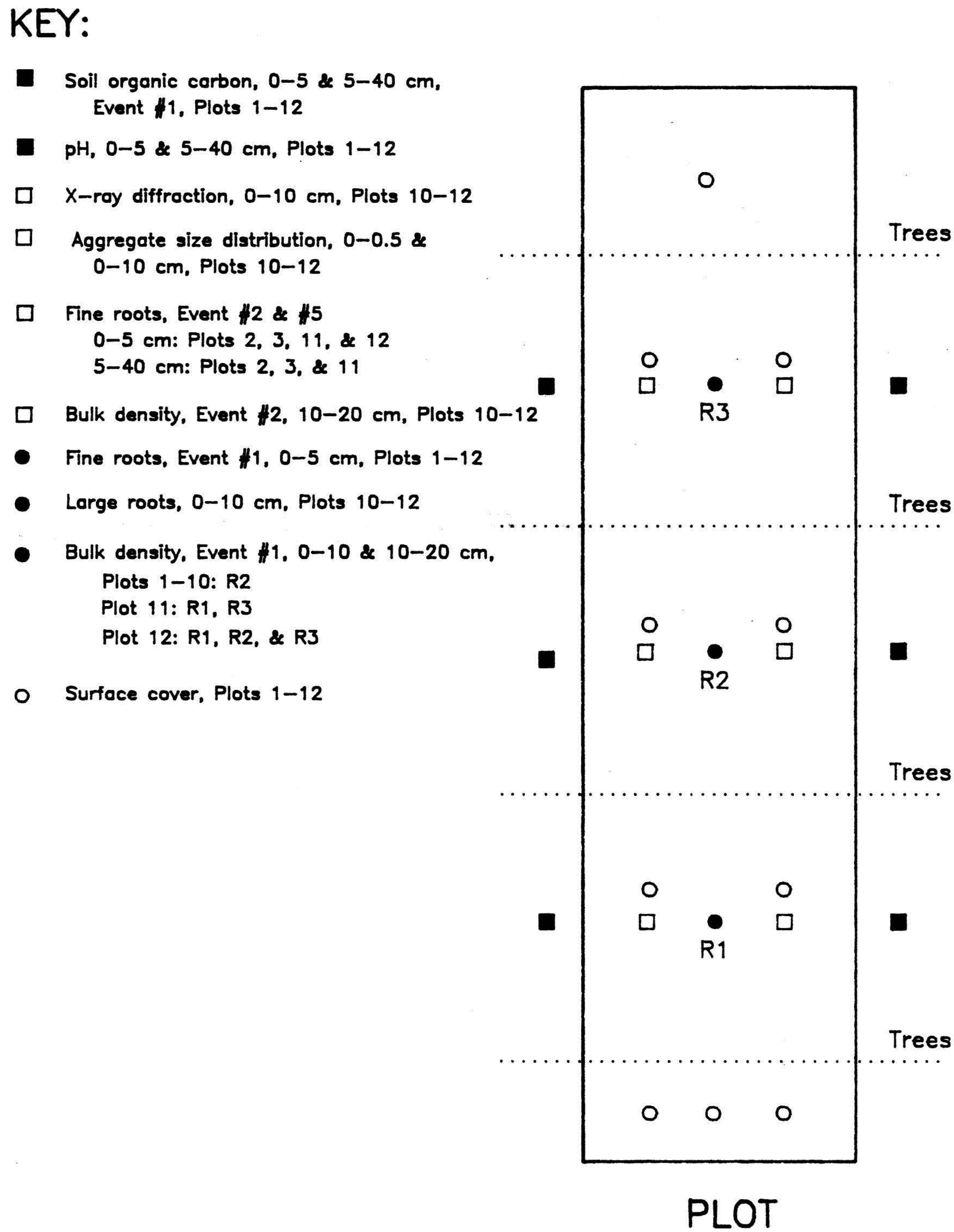


Figure 12. Soil sampling locations for parameters measured.

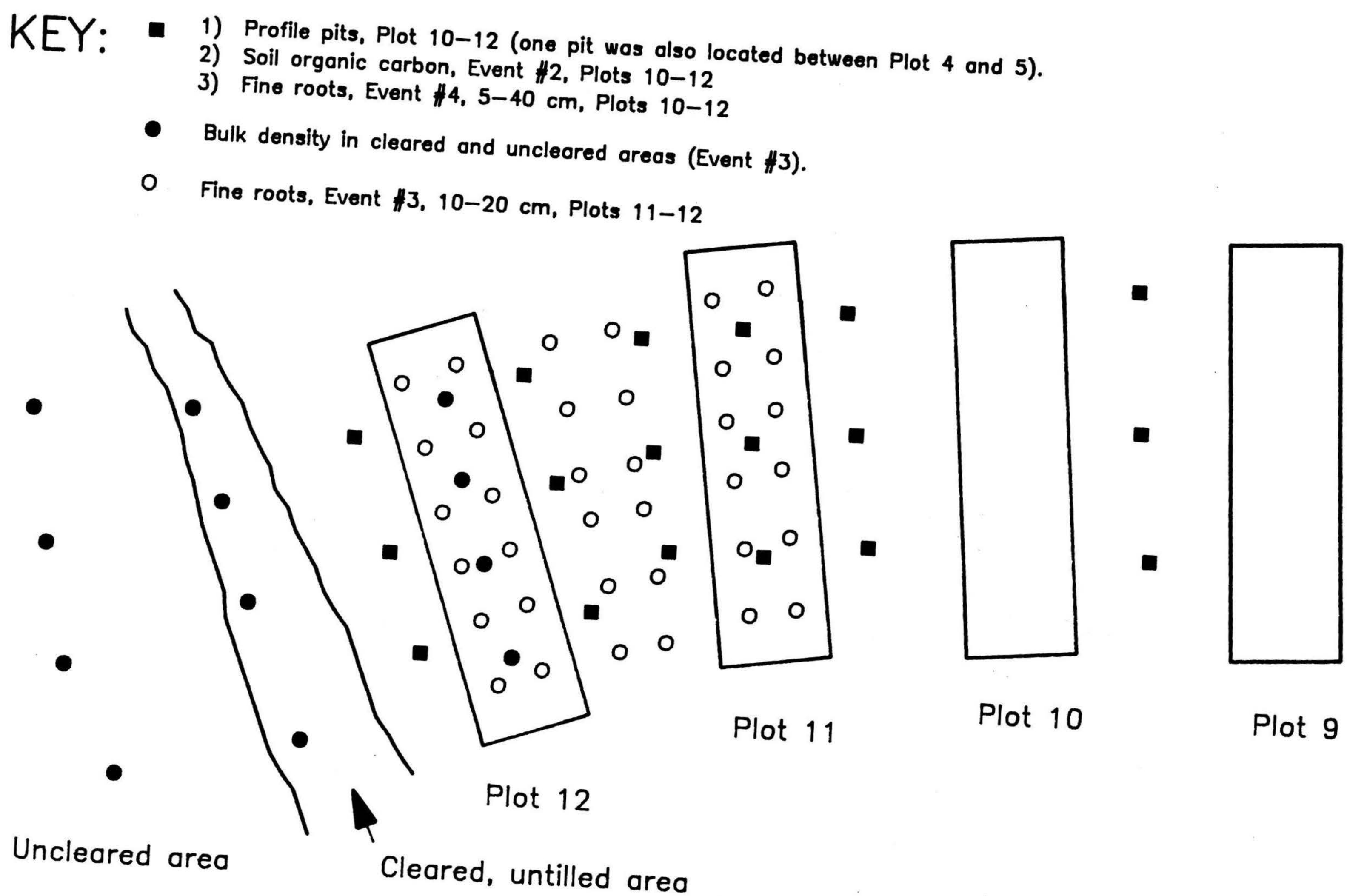


Figure 13. Soil sampling locations for parameters measured on Plots 10–12.

V. RESULTS

A. Rainfall and Erosivity

Although a rainy season and a dry season are not as distinct in Hawaii as they are in many tropical regions, the winter months tend to be wetter and have the largest and most intense storms as was the case during this period. For most of the year, the tradewinds bring the rains from the east and northeasterly direction, but during the winter months, Kona winds from the west and northwest bring colder and heavier rains (Grace and Nishimoto, 1974). The island of Kauai is affected to a greater extent than the other Hawaiian Islands because of its northwest position in the chain.

For the year long experimental period, 9/1/88-8/31/89, rainfall and EI30 Index were 327 cm and 1980 kN/h, respectively. There were 42 rainfall events qualifying as erosive storms as defined by Wischmeier and Smith (1978) for the period (Table 12). Although 61% of the rainfall fell during the winter months (November-March), the sum of the EI30 index for the same period was 88% of the total year, indicating that rainfall during the winter was more erosive per cm than that during the remainder of the year (Figure 14).

Lo et al. (1985) revised iso-erodent maps of Hawaii, utilizing 14 years of data from nearly 50 raingage stations. For the area including the Experiment Station, an EI30 index range of 870-1210 has been computed. Lo also developed an empirical equation to estimate mean annual EI30 from mean annual rainfall. The equation is

$$Y = 3.48X + 38.5 \qquad [11]$$

Table 12. Rainfall events qualifying as EI30 erosive storms

	Month	Date	Rain (cm)	EI30	
1988	SEP	16	1.4	2	
	NOV	5	4.4	12	
		6	16.1	243	ADJ
		18	2.2	8	
		20	2.1	4	
		20	1.4	2	
		27	3.0	22	ADJ
	DEC	7	2.8	5	
		14	5.5	28	
		14	3.6	59	ADJ
		17	3.9	9	
		19	3.3	6	
		20	3.0	7	
		23	1.9	6	
		25	5.6	60	ADJ
1989	JAN	12	30.1	593	ADJ
		13	4.1	42	ADJ
		16	5.3	57	ER
	FEB	10	2.0	9	
		19	2.9	6	
		20	4.2	12	
		21	3.4	9	NER
		22	9.5	144	ER
		23	3.8	25	ER
		24	9.1	136	ER
		26	28.9	315	**
	MAR	1	5.8	21	NER
		3	10.9	174	ER
		4	2.2	5	
		26	2.3	11	
	APR	5	3.4	11	
		22	3.4	7	
		25	6.8	51	ADJ
		27	3.8	12	
	MAY	24	.8	2	
		27	1.4	5	
	JUN	1	5.4	24	
	JUL	16	5.3	18	NER
		22	8.9	46	NER
		23	9.1	47	
	AUG	3	5.6	12	
		4	2.4	6	
		9	1.5	3	
		13	3.3	9	
		21	4.0	8	
	TOTAL		250	1978	

KEY:

ADJ = EI30 values which have been adjusted upward to compensate for tipping bucket underestimation.

ER = Missing EI30 values which were estimated from Equation 8.

NER = Missing EI30 values which were estimated from Equation 9.

** = Estimated from addition of 3 previous storms. Of all the estimated EI30 index values, this may be the most dubious. Rainfall distribution for the previous 5 days is only generally known on a daily basis. EI30 index was estimated for each of these days with Equations 8 and 9.

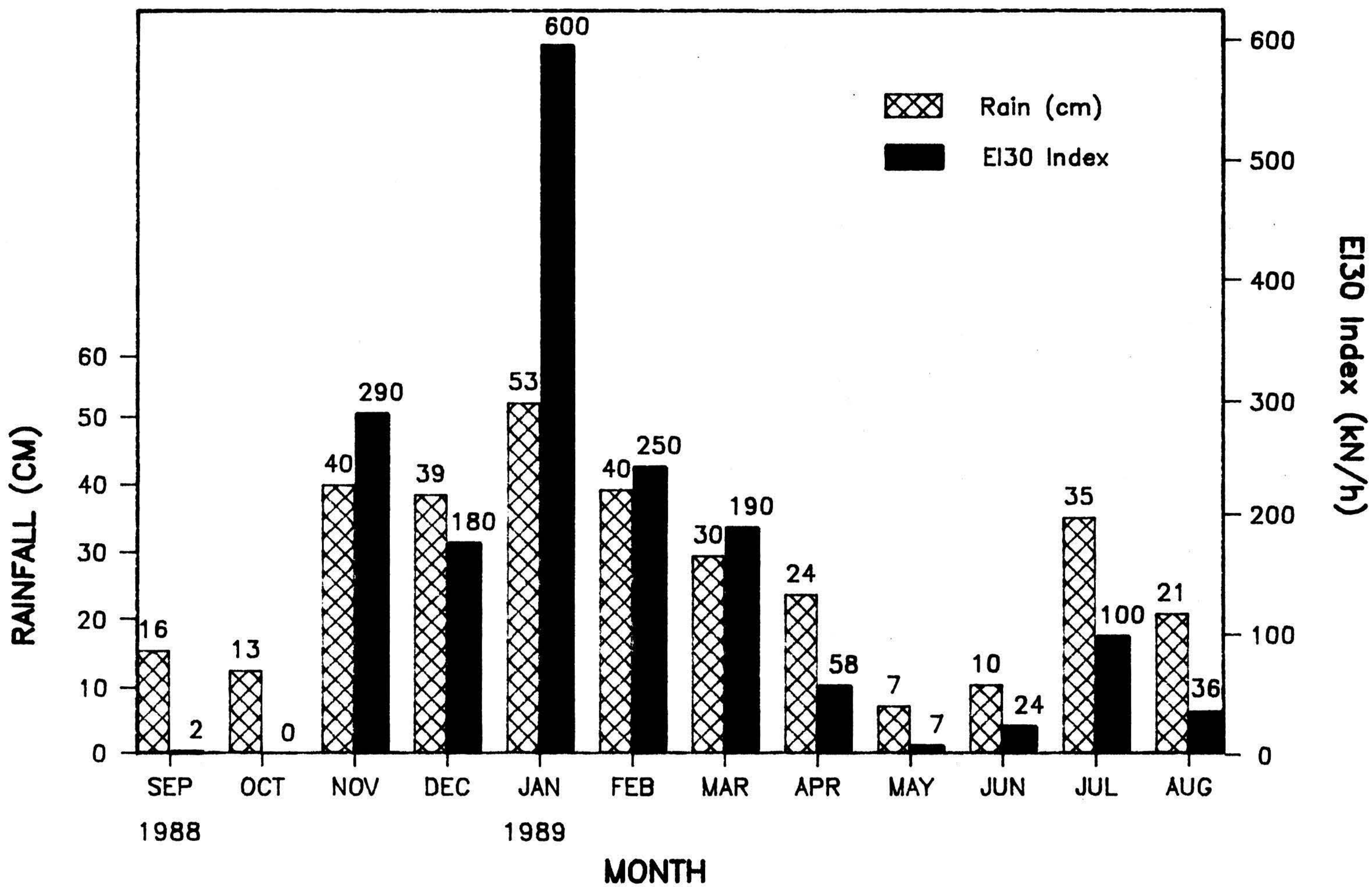


Figure 14. Monthly rainfall and EI30 Index for experiemtal period (1 year).

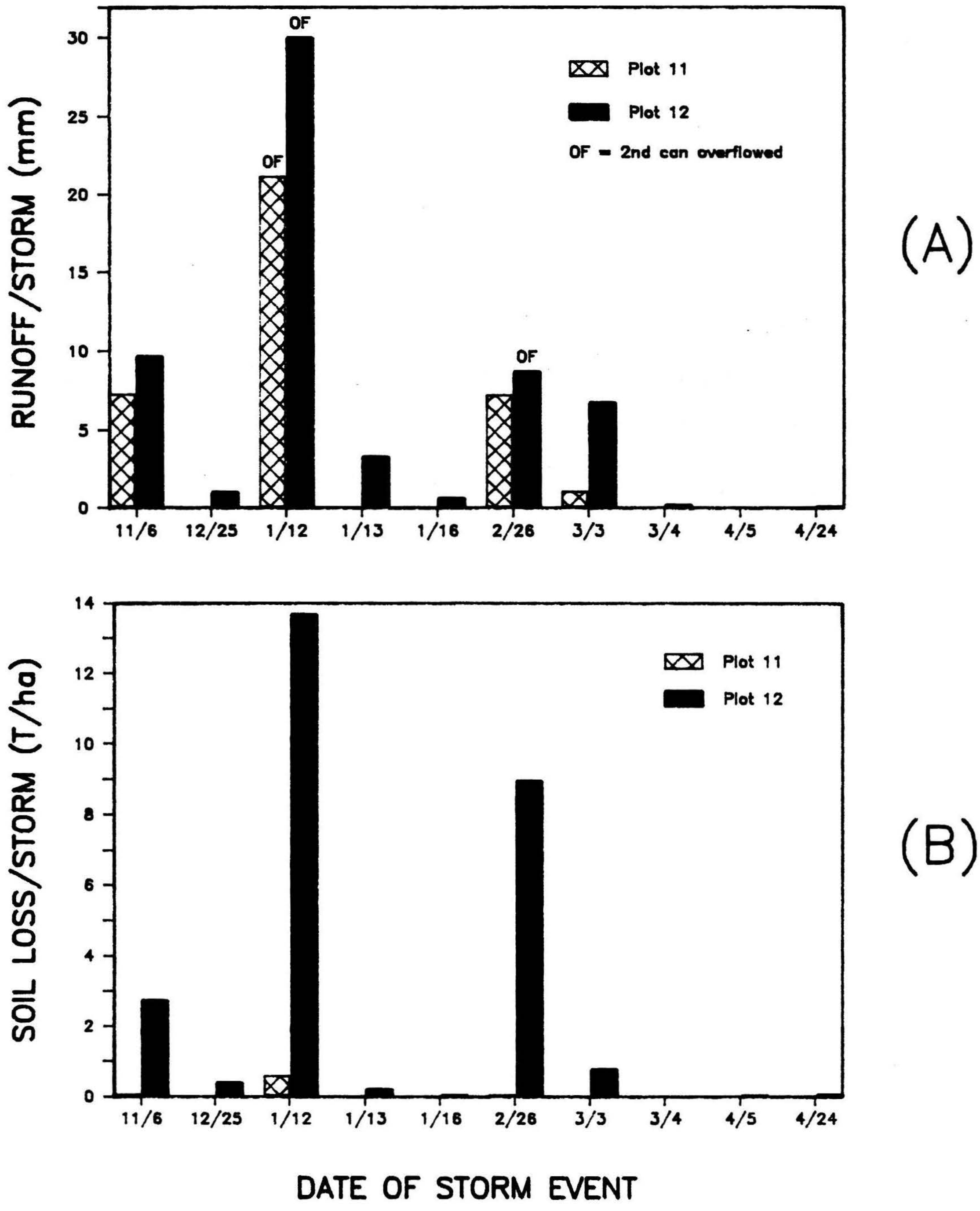


Figure 15. (A) Runoff per storm and (B) soil loss per storm for Plots 11 and 12.

where Y is equal to mean annual EI30 index, X is equal to mean annual rainfall in centimeters, and R^2 is .90. The equation predicts an EI30 index of 910 kN/h from the station's average rainfall and 1180 kN/h for the experimental period. The equation of course is not intended to predict EI30 values on an annual basis, but the value predicted, 61% of the actual value measured for the year, does demonstrate further that rainfall was particularly erosive for the experimental period.

B. Runoff and Soil Loss

Of the 42 rainfall events qualifying as EI30 storms (Table 12), runoff occurred on at least 1 plot for only 10 of these events. Despite the numerous storms, 4 of which exceeded an EI30 index value of 100 kN/h, the greatest exceeding 590 kN/h, no surface runoff occurred on 10 of the 12 plots at any time. Runoff was collected only on Plots 11 and 12. Runoff measured was equal to 1.1 and 1.9 percent of the year's total rainfall on Plot 11 and Plot 12, respectively (Figure 1). Of the total runoff on Plot 11, 100 percent occurred during the winter months and 57% of this occurred during the storm of 1/12/89. Corresponding figures for Plot 12 are 99+ and 49 percent (Figure 15A, p. 77). Runoff was consistently highest on Plot 12. There were 4 and 10 storm events when runoff occurred on Plot 11 and Plot 12 respectively (Table 13). Runoff ranged from 1.1 to at least 21 mm for Plot 11 and 0.05 to at least 30 mm for Plot 12 for corresponding storms.

As reported in Chapter 3, runoff was underestimated because of overflow problems. The 2nd can each in Plot 11 and Plot 12 overflowed for 1 and 2 storms, respectively (Figure 15A). There is, of course, no

Table 13. Runoff and soil loss events.

Date	Rain cm	EI30	Runoff (mm) Plot 11 (%)	Runoff (mm) Plot 12 (%)	Soil Loss (kg/ha) Plot 11	Soil Loss (kg/ha) Plot 12
Nov 6	16	243	7.3 (4.6)	9.7 (6.1)	76	2750
Dec 25	5	60	0	1.1 (2.2)	0	420
Jan 12	30	593	21.2 (7.1)[OF]	30.1 (10)[OF]	610	13700
Jan 13	4	42	0	3.3 (8.2)	0	230
Jan 16	5	73	0	.7 (1.4)	0	15
Feb 26	29	314	7.3 (2.5)	8.8 (3.0)	37	8980
Mar 3	11	156	1.1 (1.0)	6.8 (6.2)[OF]	2	800
Apr 5	3	11	0	.05 (.2)	0	8
Apr 24	6	51	0	.08 (.1)	0	63
TOTAL	111	153	37	61	725	27000

[OF]Indicates that the 2nd can overflowed during the storm.

way of knowing how much runoff was underestimated for these events because percent runoff varies so widely from storm to storm. It is very likely that Plot 12 is underestimated to a larger degree than Plot 11 because not only did the 2nd can from Plot 12 overflow 1 time more than that of Plot 11 but runoff on Plot 12 was consistently greater. Runoff overflowed for 1 storm which had less measured runoff than 2 other storms which did not overflow because there was already water in the collection cans from previous rain, decreasing collection capacity. For 1 event (1/12/89), the collection cans were emptied about half way through the storm to avoid overflow. Overflow error then may not be as excessive as imagined for this storm.

Soil loss measured on Plot 11 and Plot 12 was equivalent to 0.73 and 27 T/ha respectively, Plot 12 having 37 times more soil loss than

Plot 11 (Figure 1). Soil loss was measurable on Plot 12 for every storm event causing runoff. Soil loss on Plot 11 occurred as often as there was runoff, but was only measurable on 4 of these events (more than 10 kg/ha). Soil loss figures equal to about 50 kg/ha or less for a single storm are dubious because the equivalent soil measured in a container is so small that the soil may simply have been from a small clod which had fallen into the trough prior to the storm (the slope is steep). For Plot 11, 100% of soil loss occurred during the winter months, 89% of which occurred during the 1/12/89 storm. Corresponding figures for Plot 12 are 99+ and 50 percent (Figure 15B).

Although runoff did not occur on Plots 1-10, some soil was sometimes found in the containers after a rain. Water was always found in the containers after a storm regardless of runoff because all rainfall on the metal trough subsequently enters the container. It was not known whether the soil had come from clods which had simply rolled into the trough before a storm or if it represented true soil loss. Although there was no runoff, this soil loss could be from splashing of soil particles and aggregates from the bottom area of the plot immediately before the trough. Because the water in the containers appeared murky after the 11/6/88 and 1/12/89 storms in several plots, it was thought that this might have occurred for these 2 storms. In any case, total soil loss found in the cans was equal to about 5-20 kg/ha for the entire year except for Plot 6 in which a total of 60 kg/ha was measured. An arbitrary amount of soil loss for Plots 1-10 was considered to be 10 kg/ha for the year. This is equal to about 0.5 mm of soil splashed from a strip 5 cm wide at the bottom of the plot.

Assignment of a value avoids calculation of infinitely low USLE factors. Nevertheless, soil loss was very low if in fact existent.

C. Chemical Properties of the Soil

1. Soil pH

Soil pH data are presented in Table 14. There does not appear to be a pattern among plots at either depth. The surface soil was consistently less acidic than the 5-40 cm depth. Delta pH was slightly negative indicating a slightly net negative charge on the soil particle surfaces. No significant differences were found among plots at either depth. Plot 12 had a significantly lower negative delta pH than a few other plots but was not different from all plots at the 0-5 cm depth.

Table 14. Soil pH in H_2O and delta pH.

	pH in H_2O		Delta pH	
Plot	0-5 cm	5-40 cm	0-5 cm	5-40 cm
1	4.96	4.60	-0.56	-0.35
2	4.88	4.62	-0.52	-0.32
3	4.91	4.77	-0.61	-0.37
4	4.74	4.58	-0.44	-0.38
5	4.95	4.75	-0.65	-0.40
6	4.86	4.75	-0.56	-0.35
7	4.98	4.67	-0.68	-0.27
8	4.88	4.77	-0.58	-0.27
9	4.83	4.72	-0.63	-0.42
10	4.88	4.67	-0.68	-0.27
11	4.88	4.57	-0.58	-0.27
12	4.76	4.68	-0.40	-0.33
Mean	4.88	4.68	-0.57	-0.33

2. <u>Soil Organic Carbon, Event 1</u>

Soil organic carbon was originally measured to determine if alleycrop mulching affected this property. However, the data was analyzed to determine whether or not there was any correlation between soil loss and organic matter, assuming the relationship between organic matter and organic carbon was the same for all plots.

<u>Hypothesis</u>: Increased organic matter explained differences in runoff or soil loss among all plots. Therefore Plot 12 will have lower organic matter than Plot 11 which will have lower organic matter than all other plots.

Plot 11 was not found to have less organic carbon at the 0-5 cm depth than all other plots (Figure 16). Although an analysis of variance (ANOVA) found that there were highly significant differences among plots, Duncan's Multiple Range (DMR) test did not detect that organic carbon in Plot 12 was significantly less (P = .05 level) than Plots 1, 2, 3, and 7. An ANOVA for organic carbon levels at the 5-40 cm depth did not detect any differences among plots at even a 0.10 P level.

3. <u>Soil Organic Carbon, Event 2</u>

There were questions raised about the reliability of the organic carbon data for the 1st event. The soil samples contained very large amounts of fine roots which were difficult to remove from the soil. For this first set of data, the roots were not removed and the soil samples were simply run as they were taken from the plots. It was thought possible that fine root content in the samples could have inflated the figures.

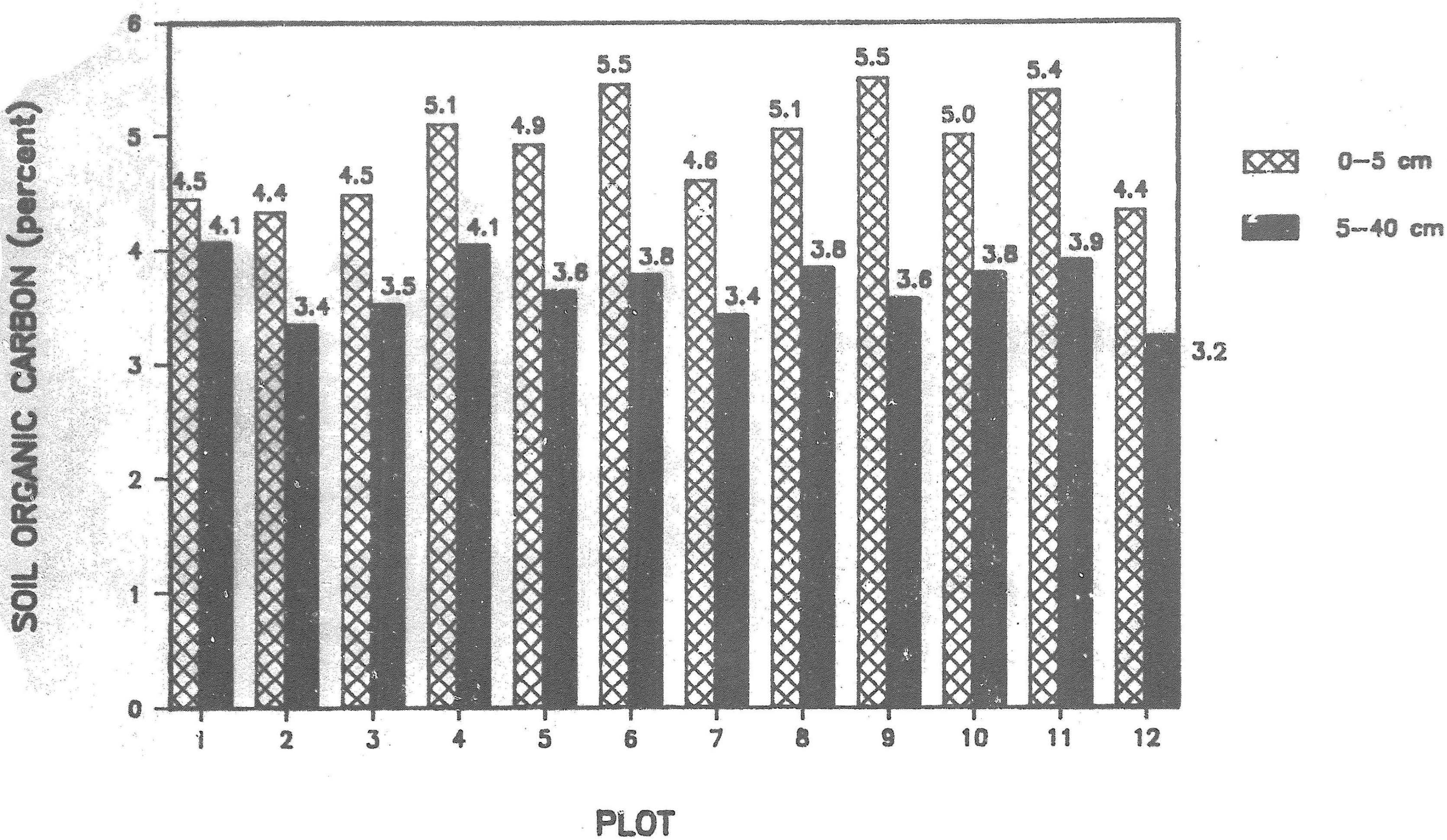


Figure 16. Soil organic carbon levels at 0–5 and 5–40 cm depth for Plots 1–12, Event #1.

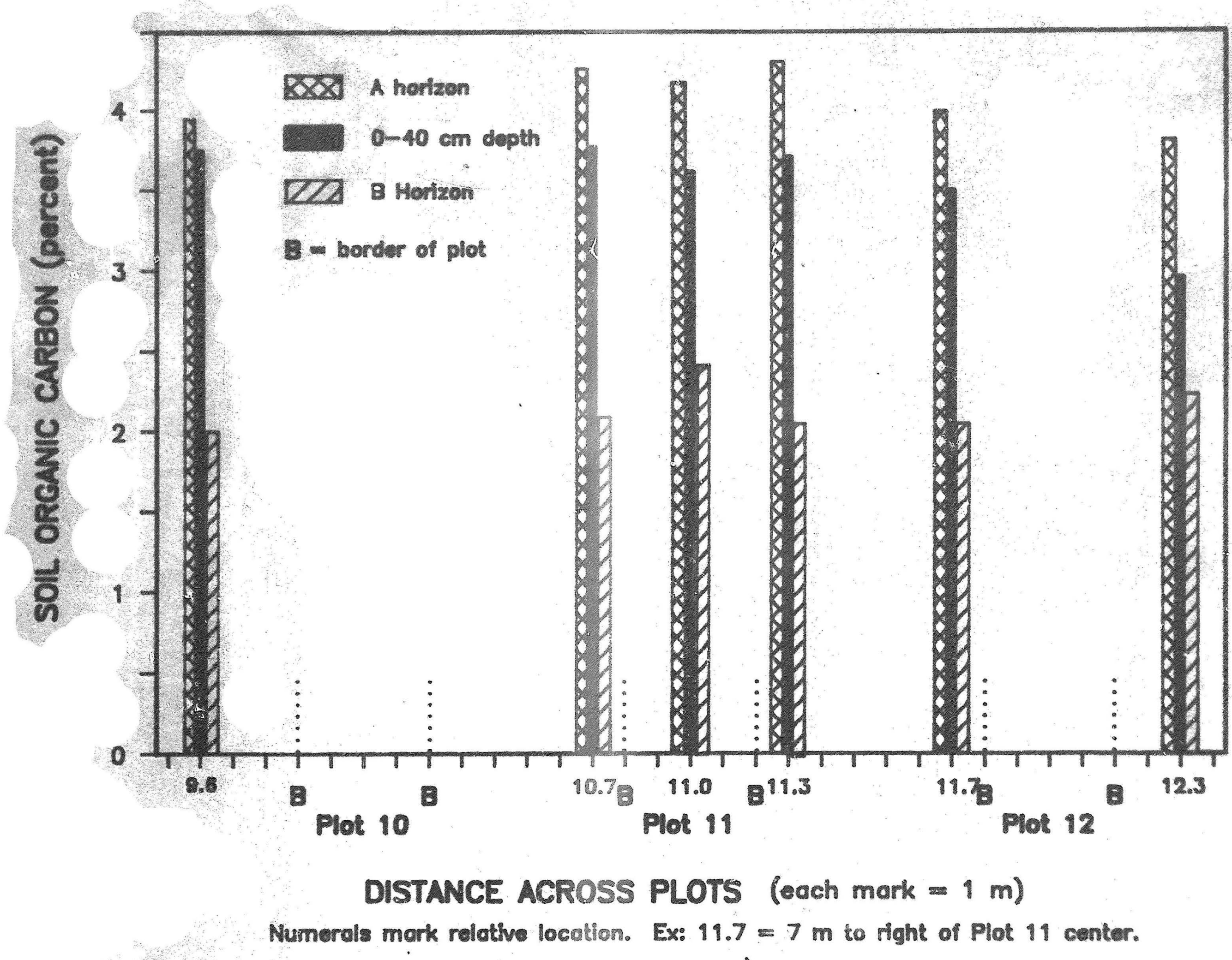


Figure 17. Soil organic carbon levels for Plots 10–12, Event #2.

Because of this uncertainty, organic carbon was measured a second time, this time removing plant matter and roots by flooding the samples with water as described in Chapter 2. This time, however, note that the depths sampled are not the same as the first set of data and that samples were taken only from Plots 10-12. The objective of this sampling was to determine if there was any correlation between organic carbon and runoff or soil loss. A secondary objective was to determine if there is a gradient between Plot 10 and 12 in organic carbon levels which might indicate that the erodibility factor of the soil changes across a gradient.

Hypothesis 1: Differences in runoff and soil loss between Plots 1-10 and Plots 11-12 can be explained by lower organic matter in the latter plots. If this is true, then Plot 12 will have lower organic carbon than Plot 11, which will have lower organic carbon than Plot 10.

Hypothesis 2: Differences in runoff or soil loss between Plots 1-10 and Plots 11-12 are not necessarily due to differences in organic carbon. However, differences in organic carbon levels explain differences in runoff and soil loss between Plot 11 and Plot 12. Plot 12 will be found to have lower organic carbon than Plot 11.

The data are presented in a histogram (Figure 17). The organic carbon level for Plot 10 is taken as the mean of Points 9.6 and 10.7 on the X axis. The Plot 11 mean is taken as the mean of Points 10.7, 11.0, and 11.3, and the Plot 12 mean is the mean of Points 11.7 and 12.3. Mean values are provided in Table 15.

There does not appear to be a pattern for the B horizon, but the A horizon and 0-40 cm depth both suggest that Plot 12 may have a lower

Table 15. Soil organic carbon (%) means of Plots 10-12, Event #2.

Plot	A Horizon	B Horizon	0-40 cm
10	4.11 a	2.06 a	3.76 a
11	4.26 a	2.26 a	3.71 a
12	3.92 a	2.12 a	3.24 a

Table 16. Comparison of soil organic carbon (%) for Event #1 and #2, 0-40 cm layer weighted.

Plot	1st Set[a]	2nd Set	Difference
10	3.95	3.76	.19
11	4.10	3.71	.39
12	3.39	3.24	.15

[a]The values for the 1st set of data were obtained by weighting the soil organic carbon levels of the 0-5 and 5-40 cm.

organic carbon level than the other two plots. However, an analysis of variance for each category failed to detect any significant differences among plots in each case, although differences were found to be statistically more probable in the A horizon (.11 level P) than in either the B horizon or 0-40 cm level.

The values are less than those obtained from the 1st set of data as expected, since plant matter has been removed this time (Table 16). The differences between the sets of data are not large. These difference could be due to the plant matter that was subsequently removed in the 2nd set of data. There was also some concern that removing plant matter by several floodings, considerable soluble organic carbon could have been lost in the process. As to which reason, if either, the error can be attributed to was not determined.

4. Mineral Analysis

Color changes evident in Figure 4 initially suggested there might be a gradient in mineralogy between Plot 10 and Plot 12. Preliminary mineral analyses by X-ray diffraction (XRD) indicated that Plot 12's mineralogy was characteristic of a less weathered and aggregated material. It appeared halloysite may be in higher quantities and more weathered minerals such as gibbsite could be lower in Plot 12 than other plots. It was hypothesized that an increase of less aggregated materials in Plot 12 and Plot 11 may help to explain differences in runoff and soil loss. Mineralogical XRD results are graphically displayed in Figure 18. Although the data represents only a single pooled sample of 6 separate samples and statistical analysis is impossible, there appears to be a distinct pattern. The XRD pattern of Plot 10 and Plot 11 are nearly indistinguishable, except for a slight increase in halloysite in Plot 11. The XRD pattern of Plot 12 indicates a sharp increase of halloysite, and a modest decrease of goethite.

D. Soil Physical Properties

1. Bulk Density, Event 1

All plots were supposed to have been prepared in the same manner as described in the section on site preparation. However, it was thought that Plot 12 and possibly Plot 11 were not disked as deep as the remaining plots. Because of the topography and steepness of the

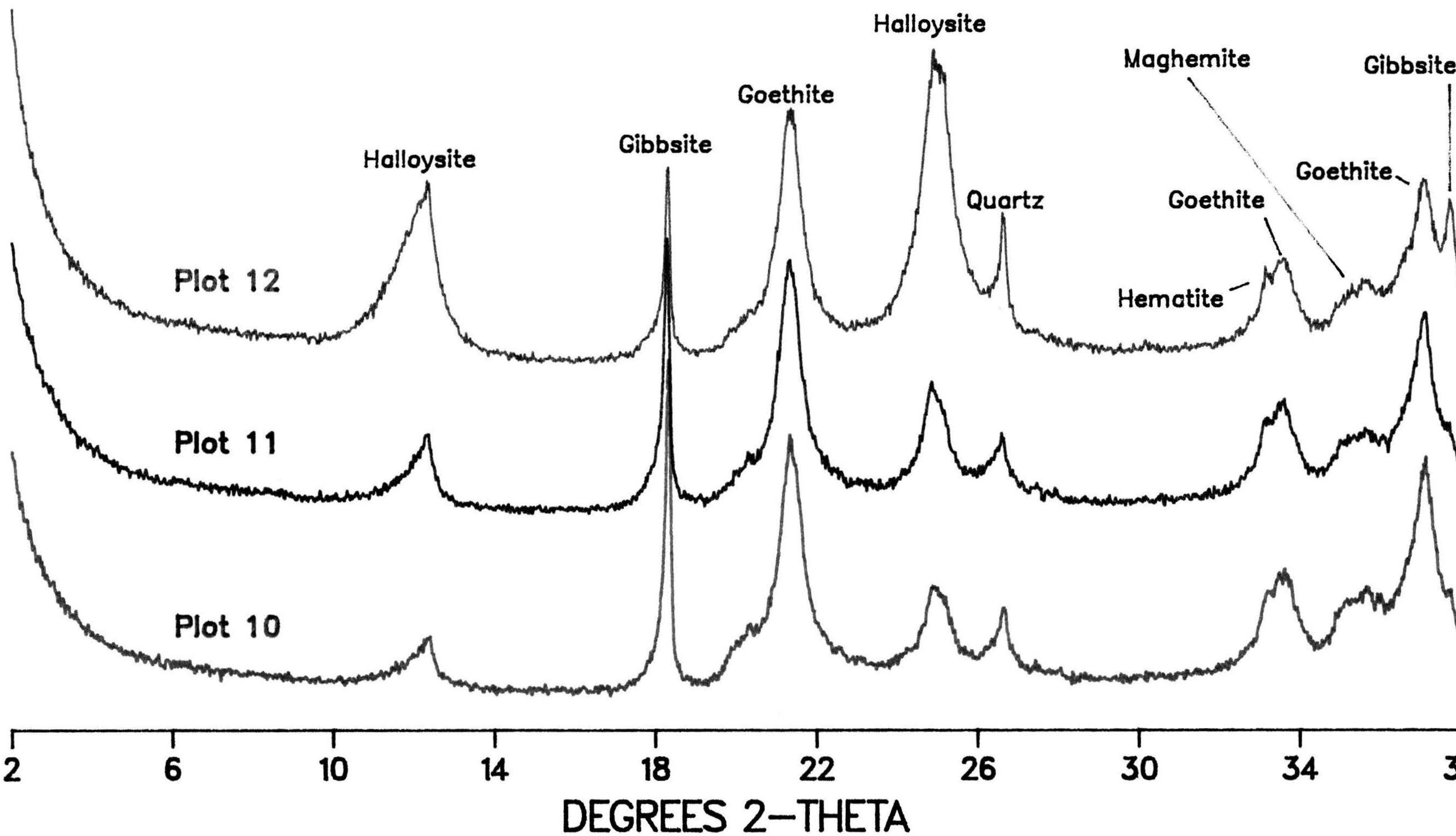


Figure 18. X-ray diffraction patterns for Plots 10-12.

experimental site area, the bulldozer operator felt it much preferable to till the site in a crosswise fashion as explained earlier. When the driver reached one end of a disking run (ending at Plot 1) he circled back to the other end of the site at the top of the hill away from the future plot locations and began another run at Plot 12. Because the driver was then coming down the plot's steep slope and making a sharp turn simultaneously while dropping his disk in Plot 12, the disk did not immediately dig deep into the soil but initially slid downhill at a shallow depth. The curved marks of the disk are visible in Figure 4. In retrospect, greater care and effort should have been taken to remedy this situation. Nevertheless, it is very probable that a thinner layer of soil was tilled near the turn then after the turn. How this situation affected runoff and soil loss became of much greater interest after the first major storm.

Soon after the first major storm on 11/6/88, visual observations of the soil loss pattern in Plot 12 were made. Soil loss appeared to be primarily if not entirely in the form of rill loss. Rills varied from 5 cm to 20 cm in width but all rills were about 10 cm in depth except for the narrowest rills. Upon examination of the soil in Plot 12, it seemed that down to that depth of about 10 cm, the soil was very loose, friable, and fairly well aggregated. But at approximately the 10 cm mark, the soil appeared less friable, wetter, less permeable, more clayey, and denser. Where there had been severe soil loss in the upper left-hand part of the border area of Plot 12, soil had been removed to a depth of nearly 10 cm in a very wide rill of 30 cm. The marks of the disk could easily be seen in the newly exposed surface. They did not go deeper than 10 cm. The soil at the bottom of this rill also appeared less friable, denser, and wetter.

It was suspected that shallower disking at this end of the site may have allowed a sort of hardpan to remain or exist on Plot 12, and Plot 11 to a lesser extent, which did not exist on other plots because they had been disked deeper and loosened. The hypothesis was that the 10-20 cm soil layer of Plots 11-12 had a higher bulk density (BD) than Plots 1-10, decreasing porosity and infiltration rates. When rainfall was excessive, the 0-10 cm layer of soil saturated in Plot 12 and Plot 11 before it did in other plots because of the effect of the 10-20 cm layer. It was further hypothesized that the 0-10 cm layer would not be very different among plots.

The data is displayed in a histogram (Figure 19, p. 92). Analyses of variance revealed no significant differences in BD between treatments for the 0-10 cm depth, wet or dry. The same test for dry BD at the 10-20 cm depth did not reveal significant differences either, though the likelihood was greater (P = 12).

Differences among treatments for wet BD at the 10-20 cm depth were significant (Table 17). The means of Plot 12 and Plot 11 were nearly

Table 17. ANOVA of wet bulk density at 10-20 cm soil depth, Event #1.

Source	df	SS	MS	F	P
Between	2	.07190	.03595	6.94	.011
Within	11	.05694	.005176		
Total	13	.12884			cv = 5.6 %

identical. Differences between Plots 1-10 and Plots 11-12 are not very large, yet the difference between the two wet means, 0.146 g/cc, is more than twice the difference between the two dry means, 0.063 g/cc. This is of some interest because it indicates the volume of large soil pores is higher in the plots with no runoff.

As is already known, porosity of large pores is much more important in determining infiltration conditions than total porosity. Effective macroporosity (EM), as defined in the methods, was calculated assuming all plots had the same particle density, 3.0 g/cc. The non-runoff plots have an EM 1.6 times that of the runoff plots at the 10-20 cm depth (Figure 20, p. 93).

2. Particle Density

The means of the samples for each plot are given in Table 18. Analysis of variance test did not detect any significant differences.

3. Bulk Density, Event 2

The primary purpose of analyzing BD was to determine if there was a significant difference between Plot 12 and Plots 1-10. It had been

Table 18. Particle density of Plots 10-12 (g/cc) at 10-20 cm depth.

Plot	Mean	1 Standard Deviation
10	3.07 a	± .021
11	3.00 a	± .0082
12	2.97 a	± .010

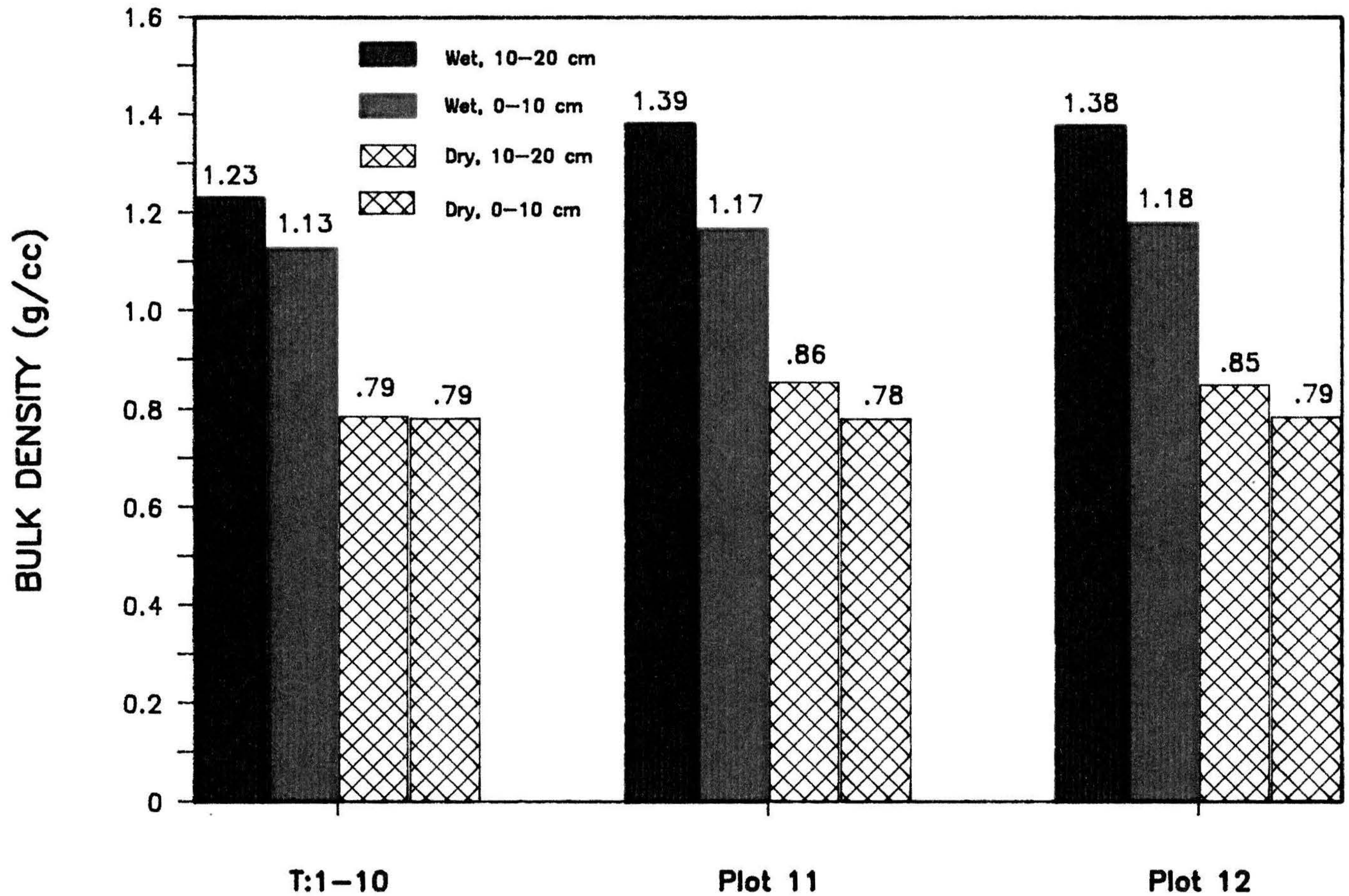


Figure 19. Bulk density at 0–10 and 10–20 cm depth for Plots 1–12, Event #1.

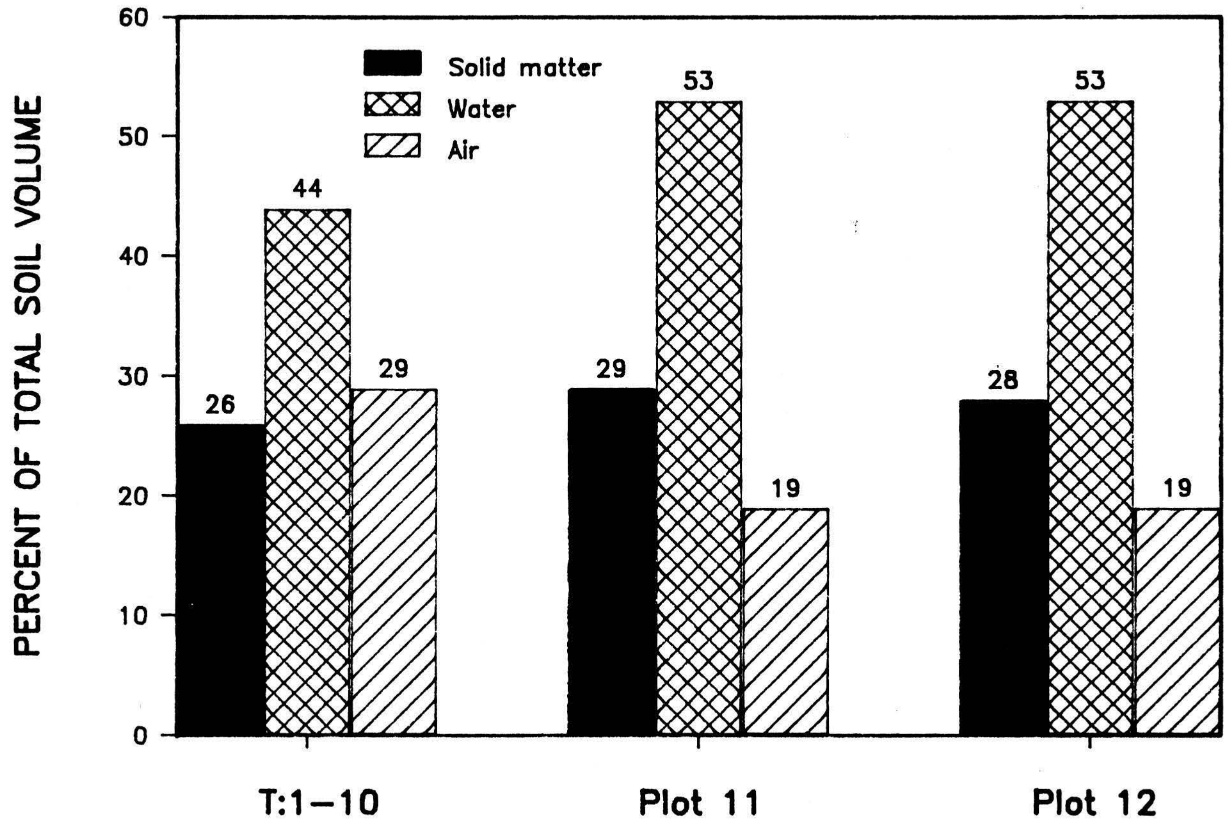


Figure 20. Volume of soil occupied by water, air, and solid matter, 10–20 cm depth. (derived from Bulk Density, Event #1)

supposed that the nature of the disking operation caused differences in BD. According to this reasoning, BD should decrease wherever the disk had sunk to its normal disking depth, occurring within 10-20 m from the point that the bulldozer and disk had straightened out. The previous BD data did test for differences in BD and EM between Plots 12 and 11 but detected none. A difference was expected but it was considered that none was detected for lack of degrees of freedom. Therefore new samples were taken. The objective however is not necessarily to only detect a difference but to reliably measure the difference. A significant but small difference may be evidence that the hypothesis is invalid or not fully explanatory of the runoff pattern. For these samples, particle density is not assumed to be 3.0 g/cc but was measured (Table 18).

Hypothesis: Differences in EM explain the runoff pattern in Plots 10-12. Because Plot 12 had more runoff than Plot 11 and Plot 10 had none, EM at the 10-20 cm depth is expected to be lowest in Plot 12, highest in Plot 10, and somewhere in between in Plot 11.

Results are presented in Table 19. An ANOVA found highly significant differences among plots for dry BD, wet BD, and EM (Tables 20-22). No significant differences were found between Plot 11 and Plot 12. Variation within Plot 11 was markedly greater than within either Plot 10 or Plot 12.

4. Bulk Density, Event 3

It was believed that bulldozing and tillage operations had actually increased soil aggregation, increasing macroporosity. Clearing the vegetation and the fern root mat exposed the surface. It was

Table 19. Bulk density and effective macroporosity, 10-20 cm depth, Event #2.

Plot	Dry	Wet	Porosity		
	-----g/cc------		Total	Water	Air
			---------percent------------		
10	.79 a	1.19 a	74.4	39.6	34.8 a
11	.85 b	1.33 b	71.8	47.8	24.0 b
12	.88 b	1.35 b	70.4	46.7	23.7 b

Table 20. ANOVA of dry bulk density, 10-20 cm, Event #2.

Source	df	SS	MS	F	P
Between	2	.02293	.001470	14.2	.001
Within	15	.01207	.0008044		
Total	17	.03500			cv = 3.6 %

Table 21. ANOVA of wet bulk density, 10-20 cm, Event #2.

Source	df	SS	MS	F	P
Between	2	.08431	.04216	16.4	.001
Within	15	.03845	.002563		
Total	17	.1228			cv = 4.2 %

Table 22. ANOVA of effective macroporosity, 10-20 cm, Event #2.

Source	df	SS	MS	F	P
Between	2	441.3	220.6	17.6	.000
Within	15	188.0	12.54		
Total	17	629.3			

hypothesized that subsequent tillage increased the macroporosity by creating a friable soil which dried and aggregated upon exposure. Thus samples were taken from the 10-20 cm depth in Plot 12 and just outside Plot 12 at 2 different nearby locations, one where the soil had not been bulldozed or disked, and one where the soil had been bulldozed but not disked. The results are displayed in Table 23 and Figure 21. An ANOVA and subsequent DMR tests found highly significant differences for each category between each treatment except in moisture between the cleared and disked area (Plot 12) and the cleared no-disked area.

Table 23. Bulk Density Samples, Event #3.

Location	Dry BD g/cc	Moisture[a] (%)	Eff Macrop (%)
Uncleared	0.69 a	0.81 a	21 a
Cleared, no-disk	0.88 b	0.52 b	26 b
Cleared, disked	0.79 c	0.44 b	39 c

[a]Moisture = mass of water/dry mass of soil.

5. Aggregate Size Distribution, Event 1

Hypothesis 1: Plots with less runoff did not saturate because the soils were better structured and well aggregated and plots with runoff saturated during certain storms because the soils were less so. Plot 12 will be found to be less aggregated than Plot 11 which will be less aggregated than Plot 10 since runoff was 1.9, 1.1, and 0 percent of total annual rainfall respectively.

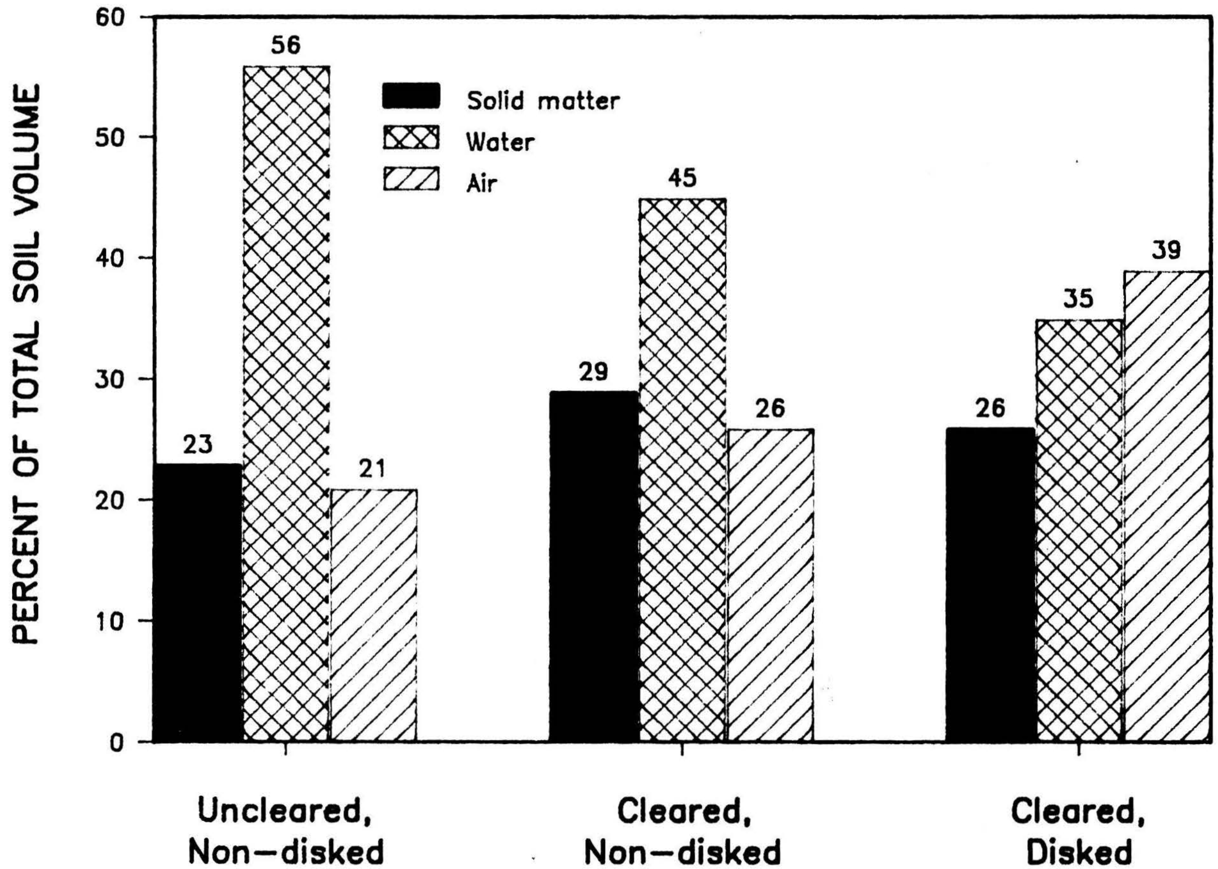
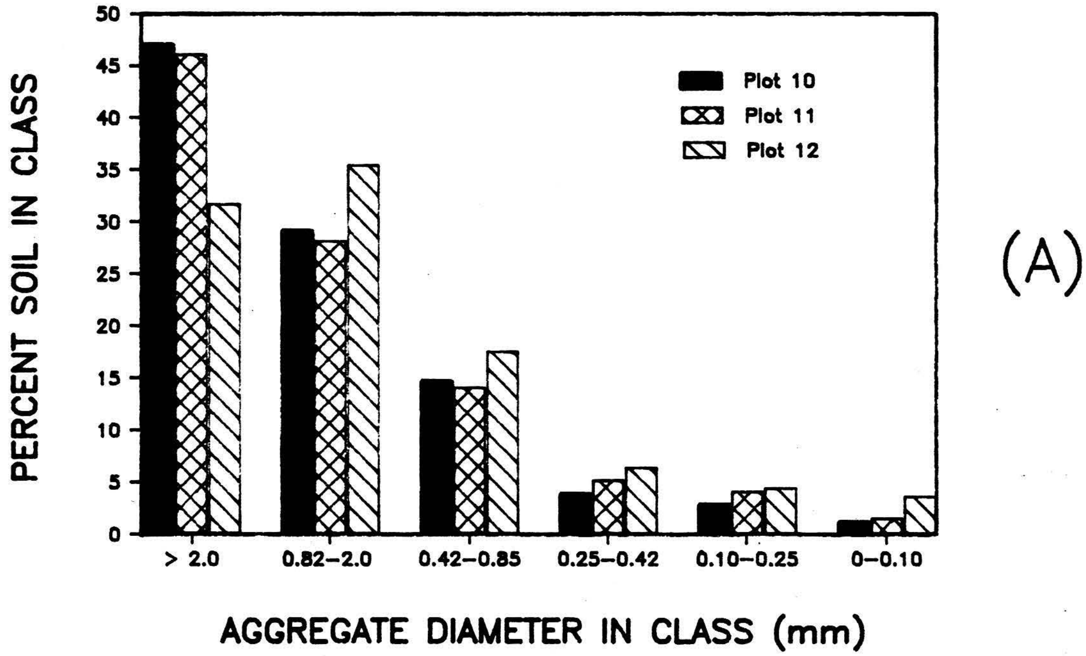


Figure 21. Volume of soil occupied by water, air, and solid matter at 10–20 cm depth for uncleared and non–disked, cleared and non–disked, and cleared and disked areas (derived from Bulk Density, Event #3).

Aggregate size distribution is a common parameter considered to indicate stability. Indexes describing aggregate size distribution generally assume larger sized aggregates indicate good soil physical structure, the larger aggregates allowing for larger and more numerous macropores (Bryan, 1968: Kemper and Chepil, 1982). High amounts of small-sized aggregates may also indicate poorer aggregation. An initial scatter plot of the percentage soil with various aggregate diameters suggests there is a distinct difference between the distribution of aggregates sizes between Plot 12 and Plots 10-11 (Figure 22A). Two frequently used indexes to describe aggregate size distribution are mean weight diameter (MWD), developed by Van Bavel (1949) and the geometric mean diameter (GMD) developed later by Mazurak (1950). Higher values for both of these parameters indicate better aggregation. MWD is the sum of products of the mean diameter of each separate size fraction sampled and the proportion of soil in the corresponding size fractions. GMD has been found to better describe most soils. It assumes that soil aggregates have an approximately log-normal rather than normal distribution, as has been shown to be the case for most soils (Gardner, 1956).

Percent oversize of each diameter fraction was plotted on a statistical X axis and the logarithm of diameter on the Y axis. However, no log-normal distribution was found when the data from Plots 10-12 was analyzed (Figure 22B). Instead, the data followed a curvilinear pattern. El-Swaify (1980) also found similar patterns with other Hawaiian Oxisols. In fact, when diameter untransformed was plotted against percent oversize for each fraction a linear equation



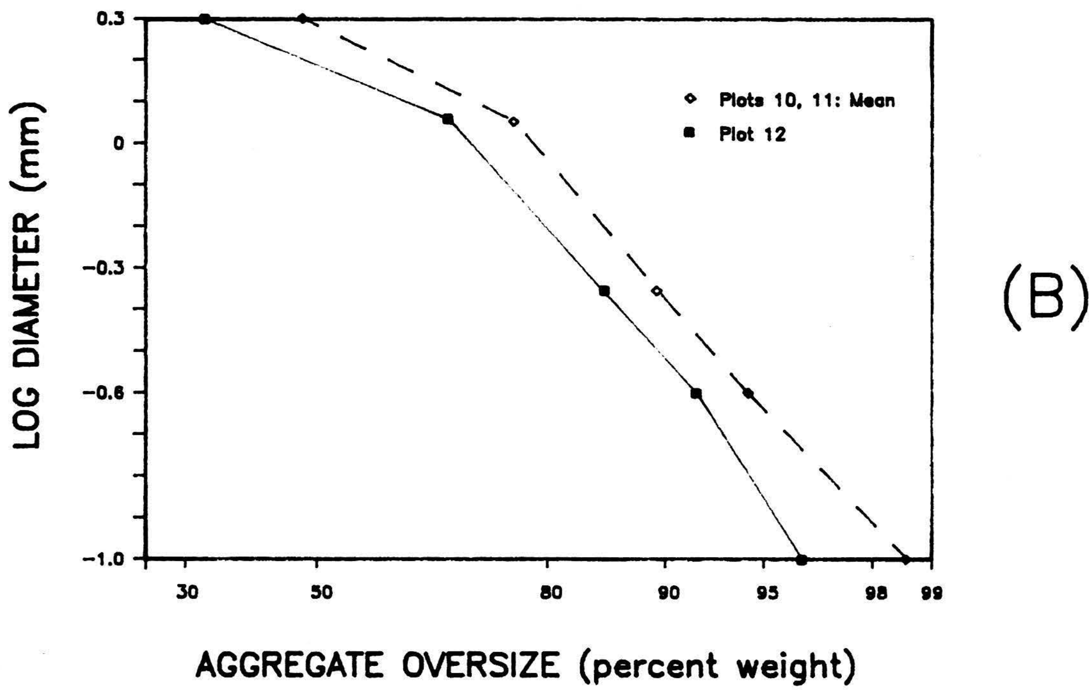


Figure 22.

(A) Percent soil in aggregate diameter class, 0–10 cm depth, Event #1.

(B) Relationship between percent aggregate oversize weight and log aggregate diameter at 0–10 cm depth, Event #1.

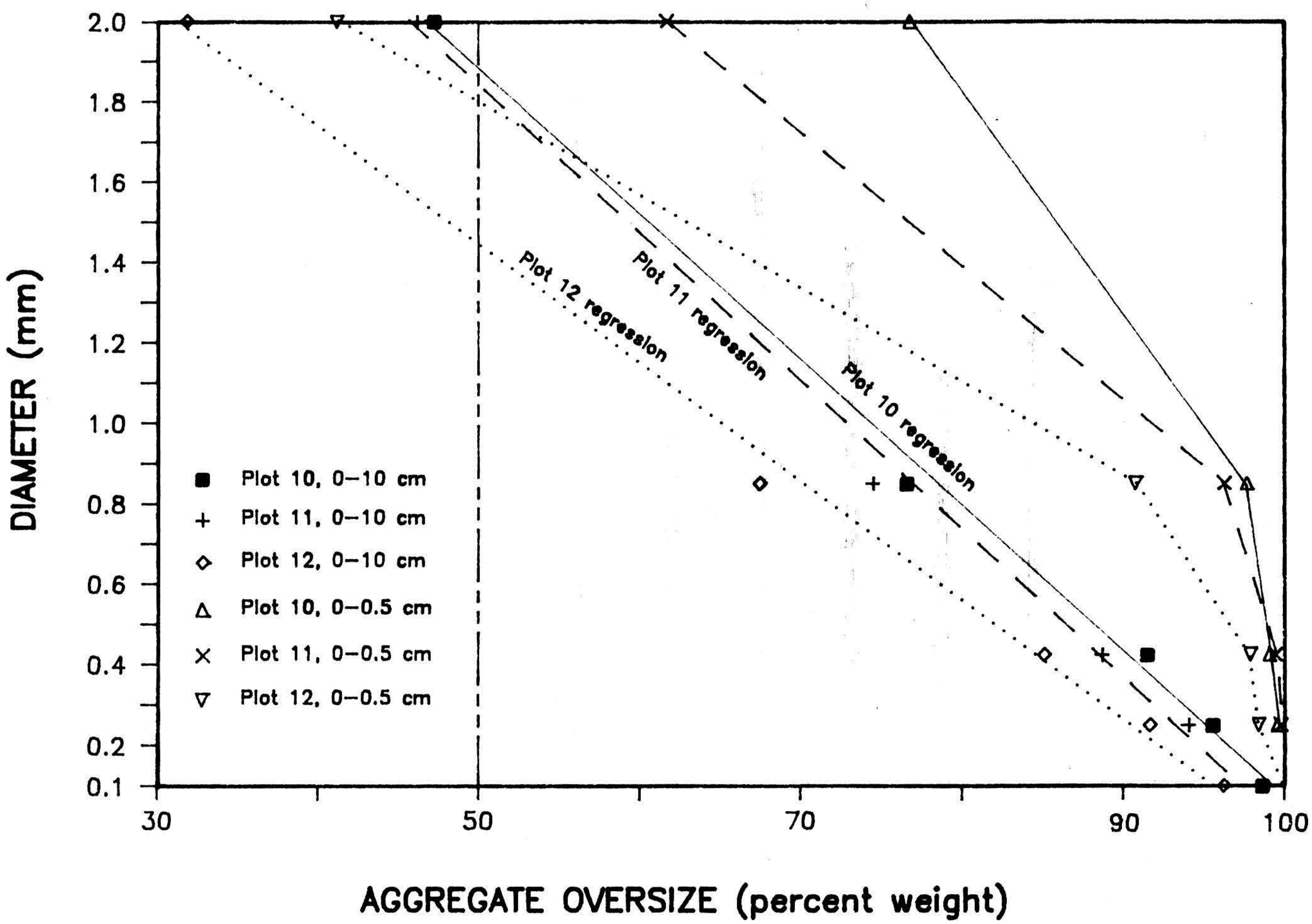


Figure 23. Scatter plot of aggregate oversize weight vs aggregate diameter for Plots 10–12 at 0–0.5 and 0–10 cm depth.

fitted the data better than a log transformed regression (Figure 23, p. 100). Computation of MWD from linear regression was considered, but for several samples the proportion of soil weight retained by a 2.00 mm sieve was more than 50%. To avoid extrapolation of the regression equations, Van Bavel's more standard MWD calculation was used instead. As a check, percent weight of aggregates over 2.00 mm was also analyzed. It should be noted that Van Bavel's MWD summation process has been found to tend to overestimate actual MWD (Kemper, 1982). Percent weight for the aggregate fraction smaller than 0.10 mm was also compared, testing a hypothesis that Plot 11 and 12 had more smaller sized aggregates. The means for each of the parameters examined are given in Table 24. Referring to Figure 23, it appears that values calculated by Van Bavel's method probably does overestimate MWD.

An analysis of variance for MWD found significant differences at the .04 P level (Table 25). Subsequent DMR tests indicated real differences between Plots 10-11 and Plot 12 probable at the .05 level, but none between Plot 10 and 11. For the percent fraction over 2.00 mm, the F-test was significant at .043 P level (Table 26). The DMR test between Plot 10 and Plot 11 again was not significant. Between Plot 11 and Plot 12, DMR test indicated differences at the .03 P level. Analysis of variance for percent soil weight for aggregates less than 0.10 mm in diameter found the F-test to be highly significant at the .006 P level. (Table 27). Using the DMR test, the difference between Plot 10 and Plot 11 means was not found significant, but the test between Plot 11 and Plot 12 was found to be highly significant.

Table 24. Aggregate Size Distribution Parameters, Events #1 and #2.

PLOT	MWD (mm)	% >2.00 mm	% <0.10 mm	MWD (mm)
	------------------0-10 cm depth-------------			0-0.5 cm
10	2.12 a	47.2 a	1.37 a	2.90 a
11	2.08 a	46.2 a	1.34 a	2.60 b
12	1.72 b	31.9 b	3.27 b	2.15 c

Table 25. ANOVA for MWD, 0-10 cm depth, Event #2.

Source	df	SS	MS	F	P
Between	2	.5718	.2859	4.37	.032
Within	15	.9810	.06538		
Total	17	1.553			

Table 26. ANOVA for percent weight aggregates over 2.00 mm, 0-10 cm depth, Event #1.

Source	df	SS	MS	F	P
Between	2	881.3	410.7	3.92	.0497
Within	15	1688	112.5		
Total	17	2569			

Table 27. ANOVA for percent weight aggregates less than 0.10 mm for 0-10 cm depth, Event #1.

Source	df	SS	MS	F	P
Between	2	23.33	11.67	7.35	.006
Within	15	23.82	1.588		
Total	17	47.15			

6. Aggregate Size Distribution, Event 2

It appeared that the surface soil (0 - 0.5 cm) was very well aggregated, much better than soil below the surface and better than when the soils were first prepared. It was considered that the surface soil on plots with runoff was less aggregated than plots with no runoff, possibly leading to some surface sealing on runoff plots. MWD was again calculated by Van Bavel's method (Table 24). The values are considerably larger than for the 0-10 cm depth. An ANOVA demonstrated that each of the plots' surface soil aggregates had a different MWD (Table 28). In general, MWD increased sharply relative to the 0-10 cm depth. Particularly for Plots 10 and 11, percent weight over 2.00 mm increased dramatically (Figure 23). The largest increase for Plot 12 was in the 0.85 - 2.00 mm category. Percentage of aggregates in all categories less than 0.85 mm in all 3 plots dramatically decreased.

Table 28. ANOVA for Aggregate Size Distribution for 0 - 0.5 cm depth, Event #2.

Source	df	SS	MS	F	P
Between	2	1.722	.8611	56.1	.000
Within	15	0.230	.01534		
Total	17	1.952			

E. Vegetal Soil Properties

1. Soil Surface Cover

The original experiment to test alleycropping effects on erosion attempted to reduce variation between all plots by preparing each plot in the same manner. Nevertheless, it was evident that surface cover, mostly from exposed roots and rock, varied to some degree from one area to another. Percent surface cover was estimated for each plot so that if variation in soil loss occurred between plots that could not be explained by treatment differences it might be possible to determine if any of the unexplained variation was due to differences in surface cover. Although the data had been taken to determine more slight variations in runoff and soil loss, the data was still examined to determine if it might be helpful in explaining the more drastic variations found.

Hypothesis 1: Surface cover partly explained runoff and soil loss variation among all plots. Thus, surface cover will be found to be lowest in Plot 12, higher in Plot 11, and greatest in Plots 1-10.

Hypothesis 2: Other factors explain lack of runoff and soil loss in Plots 1-10 as compared to Plots 11-12, but surface cover explained variation in runoff and soil loss between Plot 11 and Plot 12. Surface cover will be found higher on Plot 11 than on Plot 12.

Surface cover was quantified as percent cover by plant litter, by rock, and by plant litter and rock combined (Figure 24). The first hypothesis appears unlikely. Plots 1, 2, and 3 all have equal or higher surface cover due to plant litter than Plot 11. Plots 1, 6, and 9 all have higher surface cover due to rock than Plot 11. Combined, Plot 1 has higher combined surface cover than Plot 11.

Testing the 2nd hypothesis, a t-test was used to determine if there was a difference between means of Plot 11 and Plot 12 (Table 29). Real differences were found probable for plant matter, rock, and

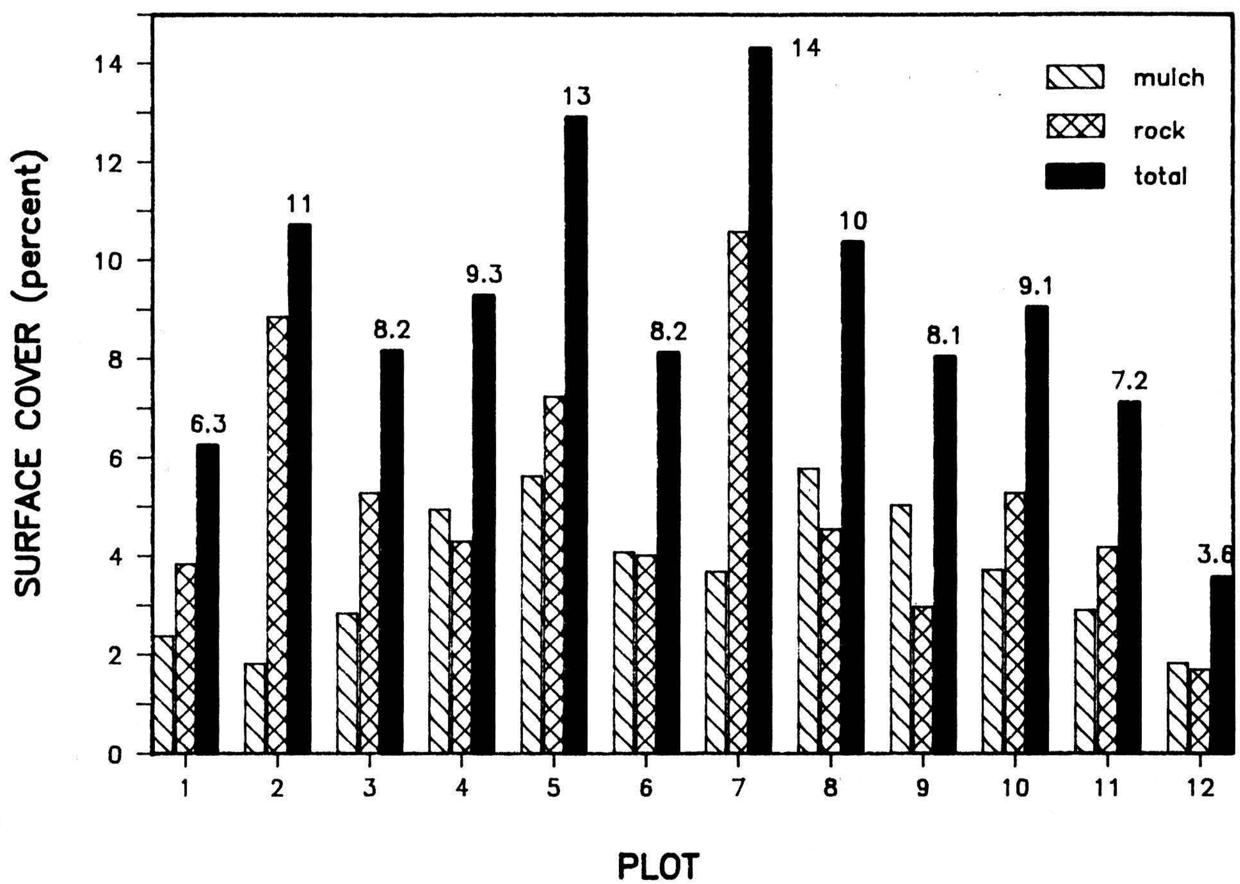


Figure 24. Soil surface cover for Plots 1–12, by mulch, rock, and mulch and rock combined.

combined surface cover at the .08, .01, and .02 P levels, respectively. There appeared to be a gradient within each plot of surface cover decreasing towards the top of the plot. A paired t-test, comparing each pair of samples in the corresponding location of each plot found real differences probable for all categories at P = .0001 level.

Table 29. Surface cover means of Plot 11 and 12.

Plot	Plant matter	Rock	Combined
	---------------------percent---------------------		
11	2.9	4.2	7.2
12	1.9	1.7	3.6

2. Fine Roots

Data was taken in 5 different events as described in Chapter 2. Visual observations in the field suggested that Plot 12 had far less root residue in the soil than other plots, particularly nearby plots. Closer observation indicated that roots tended to be predominantly of two sizes, classified fine and large roots as defined in Chapter 4. Nearly all roots appeared to be residue from false staghorn fern. Clods of soil were evident on most plots that were seemingly held together by the finer roots. Many clods, when disturbed and rolled down the steep slope several meters, did not break up. Several hypotheses were proposed to explain how roots affected soil loss and runoff. Fine roots were collected in 5 different events to test these hypotheses.

Hypothesis 1: Fine root content at the 0-5 cm depth explained differences in runoff and soil loss among all plots. The roots held aggregates together keeping them from being splashed or washed away from each other but also kept them from being compacted together. Soil aggregates were held together so well that they did not break down into smaller aggregates or fill in large pores in the soil. Therefore macroporosity and infiltration remained high. Accordingly, Plot 12 will have fewer fine roots than Plot 11 and Plot 11 will have fewer fine roots than all other plots.

Plots 2 and 3 were not found to have higher root content than Plot 11, although it appeared that Plot 12 may well be significantly lower than all other plots (Figure 25). An ANOVA of the data treating each plot as a separate treatment indicated a highly significant difference between at least 2 treatments ($P = .004$), but subsequent DMR tests found no significant difference at the $P = .05$ level between Plot 12 and Plots 2, 3, and 11 (Table 30). Because the lowest sample value of Plots 2, 3, and 11 was at least twice as high as the highest sample value of Plot 12, it was thought that there could indeed be a difference but it was not detected because of too few degrees of freedom. Therefore, new and more samples were taken from Plot 2, 3, 11, and 12 and an ANOVA run on these data (Table 31). The F test was highly significant and subsequent DMR tests found highly significant differences between Plot 12 and Plots 2, 3, and 11 (Table 32).

Hypothesis 2: Differences in soil loss between Plot 11 and Plot 12 were explained by differences in fine roots. Despite considerable runoff on Plot 11, soil loss was minimal because high fine root content

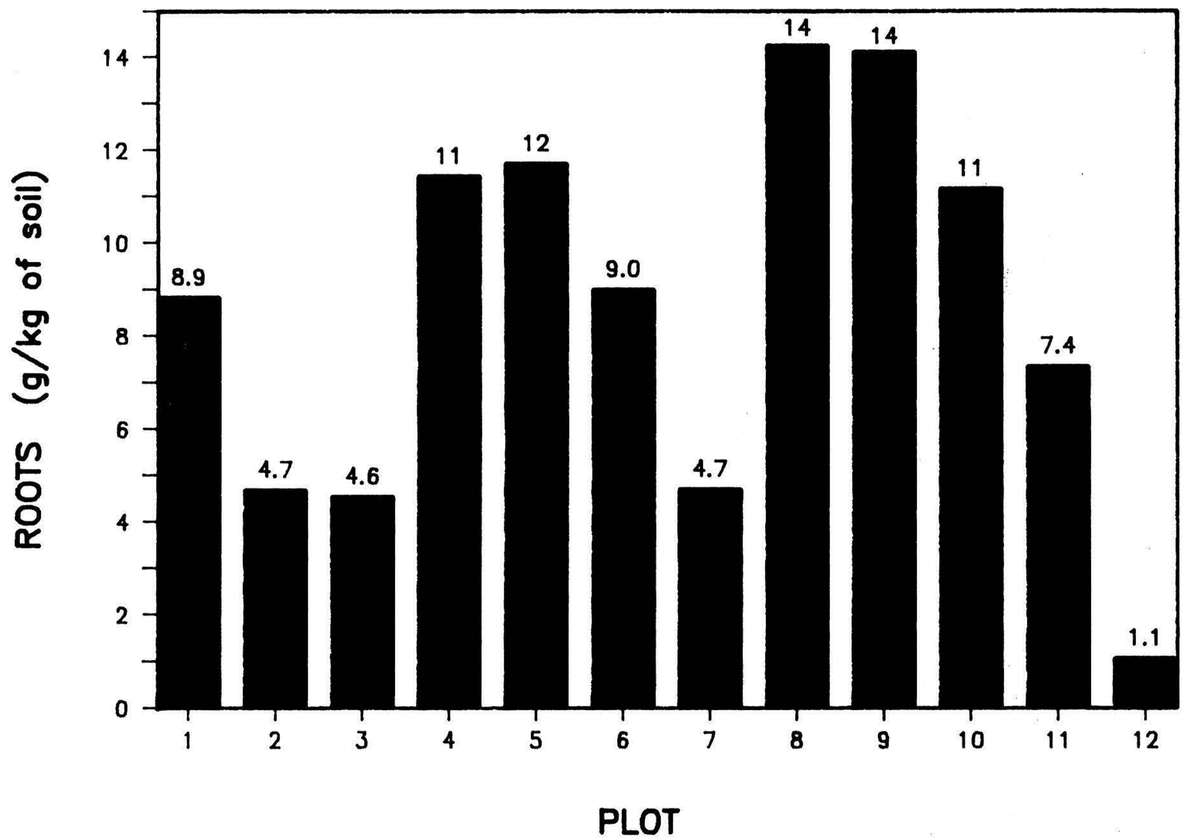


Figure 25. Fine root content at 0–5 cm depth for Plots 1–12, Event #1.

Table 30. Fine root content in the soil, 0-5 cm depth, (g/kg of soil) and Duncan's Multiple Range test, comparing Plot 12 against all other plots, Event #1.

Plot	Mean	
12	1.1	
3	4.6	
2	4.7	
7	6.7	
11	7.4	
1	8.9	*
6	9.0	*
10	11.2	*
4	11.5	**
5	11.8	**
9	14.2	**
8	14.8	**

Table 31. ANOVA for fine root content of Plots 2, 3, 11, and 12 (0-5 cm depth), Event #2.

Source	df	SS	MS	F	P
Between	3	315.3	105.1	57.17	.000
Within	32	58.82	1.838		
Total	35	374.1			

Table 32. Fine root content in the soil for Plot 2, 3, 11, and 12 at the 0-5 cm depth (g/kg of soil) and Duncan's Multiple Range test of means, Event #2.

Plot	Mean	.01
12	.87	a
2	4.6	b
3	4.7	b
11	8.1	c

on the surface bound aggregates together preventing soil loss. Fine root content in Plot 11 at the 0-5 cm depth should be found to be considerably lower than in Plot 12. The previous data already indicates this may be true. Visually it appeared that fine root content sharply increased going from Plot 12 towards Plot 11 and through Plot 11. A secondary objective of this 2nd set of data was to determine if a gradient in fine root content existed between Plot 11 and Plot 12.

There appeared to be a definite sharp gradient between Plot 11 and Plot 12 (Figure 26), fine root content significantly decreasing in the direction of Plot 12 (Table 33).

Table 33. ANOVA for Plot 11 and Plot 12, 0-5 cm depth, Event #3.

Source	df	SS	MS	F	P
Between	1	315.2	315.2	222	.000
Within	22	31.22	1.419		
Total	23	346.4			

Hypothesis 3: Differences in runoff between Plots 1-10, 11, and 12 can be explained at least in part by differences in fine root content through a deeper depth. Fine roots enhanced soil structure, allowing for higher infiltration rates. If this were the case, fine roots at the 5-40 cm depth (extends through the A horizon) may be found to be lowest in Plot 12, higher in Plot 11, and highest in Plot 10.

A histogram of fine root content across distance indicates that there is a gradient at the 5-40 cm depth through Plots 10-12, but the

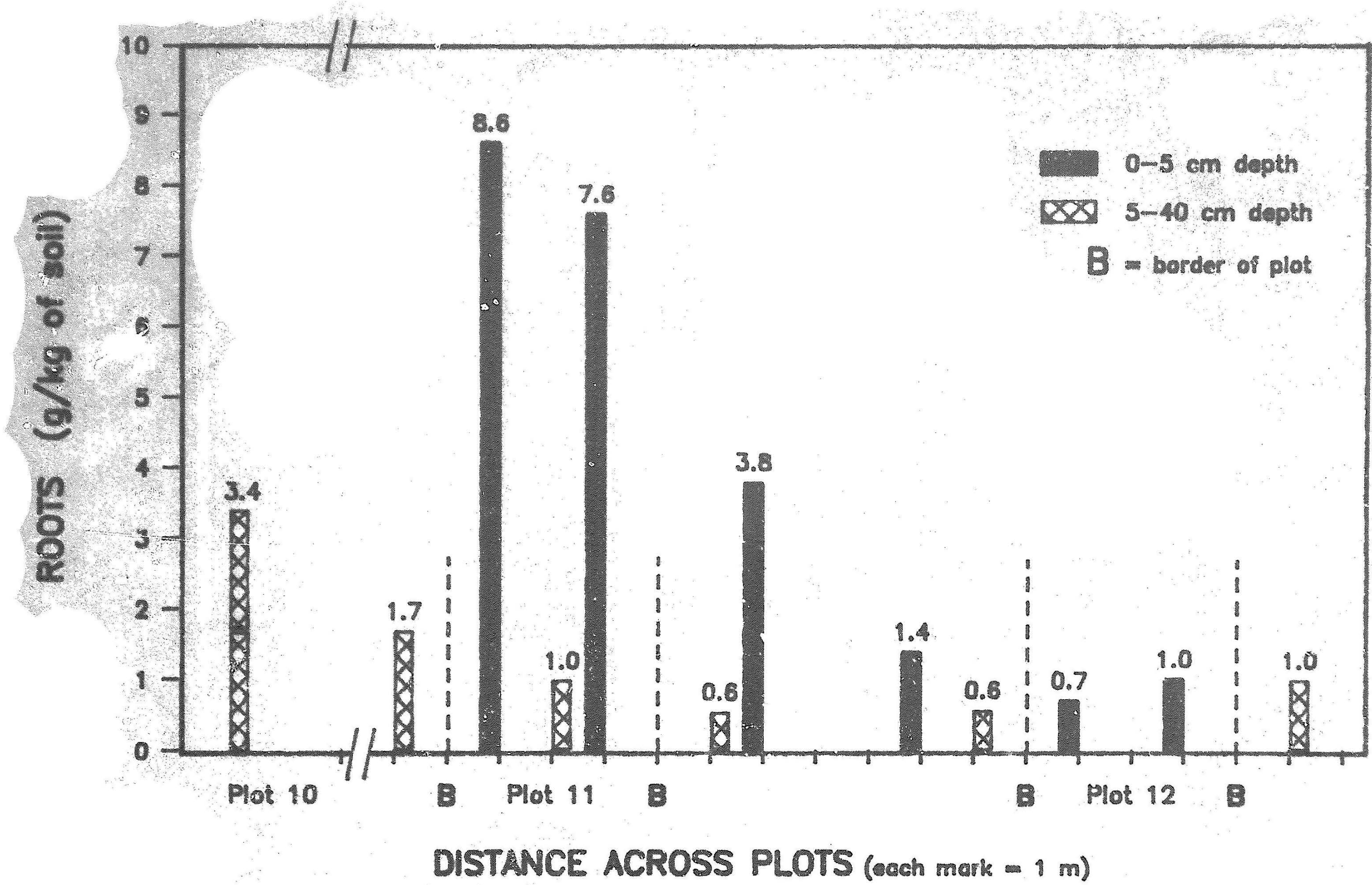


Figure 26. Fine root content at 0–5 and 5–40 cm depth for Plots 10–12, Events #4 & #5.

gradient is not nearly as sharp as that of fine root content in the 0-5 cm layer (Figure 26). There is a sharp drop going from Plot 10 to Plot 11, and decreases more gradually continuing towards Plot 12. An ANOVA was run on the data. The F-test was highly significant (P = .002). DMR test comparison of the treatments indicated highly significant differences between Plot 10 and Plots 11-12 but none between Plot 11 and Plot 12 (Table 34). To confirm this hypothesis, fine root content in Plots 1-10 must each be higher than Plot 11. Plot 11 was compared against Plots 2 and 3 first since these plots had lower fine root content at the 0-5 cm depth than Plot 11. Both plots were found to have fine root content less than Plot 11 (Table 34).

Table 34. Fine root root content of Plots 2-3 and 10-12 at 5-40 cm depth (g/kg of soil) and Duncan's Multiple Range test of means, Event 5.

Plot	Means	.05 P	.01 P
10	2.54	a	a
11	1.05	b	b
12	.80	b	b
2	.72		
3	.56		

3. Large Roots

Visual observations were made that Plot 12 appeared to have less large root content than Plot 11. It was hypothesized that these roots had contributed to stabilizing the soil structure, controlling soil loss. Large root content in Plot 12 should be greater than in Plot 11, which should be greater than all other plots. Large roots did not appear to be nearly as numerous and evenly spread throughout the plots. Several plots appeared to have considerably lower large root content than Plot 11.

An ANOVA and subsequent DMR tests detected no difference between Plot 12 and Plot 11 at P = .05 level, but Plot 10 was found to have a lower large root content than Plot 11 (Table 35). There was high variation in Plot 11. The sample from the top third of the plot, R3, is only 0.68, g/kg while two lower samples, R1 and R2, are 3.36 and 2.64 g/kg at the 0-10 cm depth (Figure 12).

Table 35. Dry large root content (g/kg of soil) and Duncan's Multiple Range test of means.

Plot	Mean	P =.05	P =.01
12	.23	a	a
10	1.24	ab	ab
11	2.23	b	b

VI. DISCUSSION AND CONCLUSIONS

The modified objective of this thesis was to simply explain as much as possible the results of soil loss and runoff, the pattern of which is depicted in Figure 1, specifically answering the questions:

1. Why was there no runoff or soil loss on Plots 1-10 and considerably less on Plots 11 and 12 than predicted by the USLE model?

2. Why was there runoff on both Plots 11 and 12 when there was none on Plots 1-10?

3. Why was there such greater soil loss, and runoff to a much lesser extent, on Plot 12 than Plot 11?

A. QUESTION 1: Why was there no runoff or soil loss or Plots 1-10 and considerably less on Plots 11 and 12 than predicted by the USLE model?

This, perhaps, was the most perplexing question. There was essentially no soil loss or runoff on Plots 1-10 despite steep slopes and the occurrence of several storms with high erosivity values. The USLE model, with the assumed factors, predicts 22, 510, and 33,000 times the actual soil loss on Plot 12, Plot 11, and Plots 1-10,. Even Plot 12 and Plot 11 experienced considerably less soil loss than predicted.

For runoff to occur, rainfall must exceed the soil's infiltration capacity. This can occur when the rainfall rate exceeds the soil's saturated hydraulic conductivity or when the surface seals to the point that the infiltration rate is restricted enough to be less than the rainfall rate. Since there was no runoff on these first 10 plots, it is assumed that neither occurred on these plots. Without runoff there is of course little or no soil loss. Infiltration rates obviously are very high since there were several large storms with high EI30 values. The structure of these soils must be such that there is a matrix of large diameter interspaces between the soil particles indicating that aggregation and macroporosity are both high.

Very strong surface aggregation resistant to slaking and disintegration during heavy rain will create a surface which is resistant to sealing. On a standard USLE fallow plot used to determine K values for a soil, the soil is tilled often to prevent sealing or caking of the surface. The soil on this site was disked twice when the plots were established and the surface subsequently leveled and smoothed by raking. This certainly is not the same action as rototilling up and down the slope as is normal on standard fallow plots, but the surface was considerably broken up. Yet, there was no evidence that caking or sealing occurred on Plots 1-10.

The question is what allows the soil, both on the surface and beneath, to aggregate so well that the very high infiltration rates are obtained during a storm. There are several possibilities. Aggregation could be due to inherent properties of the soil which cause it to aggregate. High organic matter correlates positively with good structure. Certain hydrous minerals are also known to contribute to good structure. High root content was suspected of binding aggregates together. These factors may be additive.

1. <u>Mineralogy and Soil Organic Matter</u>

Anionic Acrudox soils by definition are highly weathered and tend to have high organic matter content. The Halii soil has developed over an easily weatherable parent material of melilite basalt containing relatively low silicon content. High rainfall and constant warm temperatures have been important factors leading to extreme weathering, leaving behind a soil predominant in iron and aluminum oxides. The wet tropical location on the windward side of Kauai is particularly conducive for the development of a humic and highly weathered soil.

Soils high in organic matter and Fe and Al oxides are known to have very low erodibilities (Chapter 3). Analyses of soil organic carbon found high levels of organic carbon on all plots (Figure 16 and Tables 15 and 16). Assuming a factor of 2 to convert organic carbon to organic matter (Nelson and Sommers, 1982), organic matter is in the range of 4-9% for the A and B horizons and 9-11% for the 0-5 cm depth.

The XRD analyses of soil samples from the experimental site revealed high levels of gibbsite, goethite, and some hematite, all very resistant minerals. Concretions of goethite, gibbsite, and halloysite are so predominant on this site that pieces from a few millimeters to 15 cm in diameter are visibly seen strewn about the surface.

2. <u>Stable Aggregation Upon Dehydration</u>

Erodibility factors estimated for the Anionic Acrudox take into account high organic matter and resistant soil materials. In general, the K factor, 0.13, estimated by SCS (1976) may be fairly representative of this soil and normally an adequate predictor of soil loss.

However, when the soil was left very exposed to drying as were all the plots during the first 9 months, it was found to aggregate well and stay aggregated. An SCS soil scientist examined and described 5 different profiles on Plots 5, 9, 10, 11, and 12 (Appendix 2). Upon several minutes of rubbing the soil with water between one's fingers, many soil aggregates did not break down. He described the soil as irreversibly dehydrating in the upper 1-2 cm of the surface, as the soil is classified (Soil Survey Staff, 1972). These soils do not dry irreversibly to the same extent as more truly irreversibly drying soils such as the more well-known Hydrandepts or plinthite which forms a stone-like material upon drying. However, this soil does exhibit properties somewhat similar to irreversible dehydration in that surface aggregates remain stable and intact despite being wetted and constant gentle friction and pressure is applied. To avoid confusing the dehydration properties of the Halii soil with the properties of plinthite or Hydrandepts, the term irreversible dehydration will not be used here for the Halii soil. Instead, this property will be called dehydrated stabilized aggregation (DSA).

Aggregate size data demonstrated that there was a statistically significant and large increase in the size of surface aggregates for Plots 10-12 ($P = .05$). On the surface, 0-0.5 cm depth, 95% weight aggregates were greater than 0.85 mm in diameter, but only 73% for the 0-10 cm depth. Note the sharp shift of the relationship between aggregate oversize weight and diameter (Figure 23).

There is other indirect evidence to indicate that DSA on the surface was an important factor. Because no runoff occurred on Plots 1-

10, we know that neither the saturated hydraulic conductivity rate was exceeded nor did the surface significantly slake or seal. Since Plots 11 and 12 did have runoff, the surface of these two plots must have sealed or the soil more than saturated or both. But the pattern of runoff for Plot 12 does not indicate that the surface sealed. Generally, when a surface seals it would be expected that the soil would be more likely to have runoff in subsequent events. However, there was no apparent relationship between runoff and sequence of rainfall events. A look at the pattern of runoff on Plot 12 during all rainstorms indicates that runoff does not usually occur until EI30 is above about 40-50 kN/h (Figure 27). Above this point, runoff linearly correlates with EI30. For Plot 11, the relationship is similar but shifted, runoff occurring only when EI30 exceeds 100 kN/h. The general pattern indicates that runoff is less likely due to surface sealing but that rainfall simply exceeds the infiltration rate at a certain intensity. There is an exception, the 1/13/89 storm (labelled #4 on graph) on Plot 12. This probably is explained by high antecedent moisture. The storm occurred soon after the largest storm of the year (Table 12), a storm for which rainfall was 30 cm and the EI30 index was nearly 600 kN/h.

Normally, the direct impact of raindrops breaks down the soil structure of the soil (Chapter 3). The DSA property of this Halii soil apparently severely restricted the surface soil from slaking or sealing even during heavy rainstorms. Instead of causing increased disintegration of aggregates, tillage and exposure of the soil to the weather was an important interacting factor triggering the DSA result.

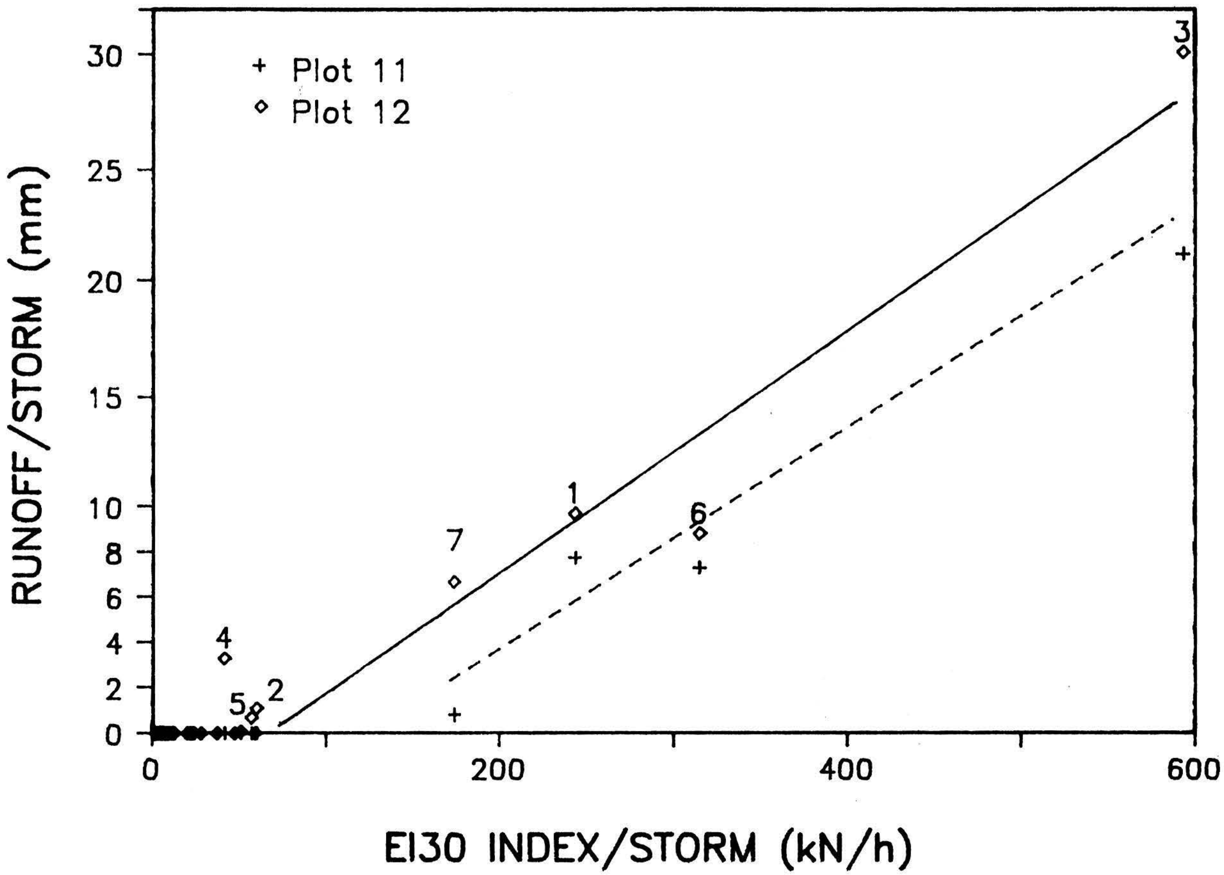


Figure 27. Scatter plots of runoff/storm versus EI30/storm for Plot 11 and 12. Storms are numbered in chronological order. Lines represent regressions of storms causing runoff only (Storm #4 is excluded for Plot 12). Storm #4 occurred immediately after Storm #3.

3. Roots

It was considered that fine roots could be binding the surface aggregates together in a stable fashion, explaining lack of runoff in Plots 1-10. But Plots 1-10 did not have less root content in the 0-5 cm depth than both Plots 11 and 12 (Figure 25).

B. QUESTION 2: Why was there considerable runoff on both Plots 11 and 12 when there was none on Plots 1-10?

If interaction between tillage and the DSA property coupled with the already normally low erodibilty of the soil explain lack of runoff on Plots 1-10, then why is there runoff on Plots 11 and 12? There must be some parameter or parameters that are consistently and considerably different between Plots 1-10 on the one hand and both Plots 11 and 12 on the other that explains the differences in runoff between these two areas.

There was little evidence that levels of organic matter in Plot 11 contributed to higher runoff than in Plots 1-10 (Figures 16-17). In fact, the organic carbon mean for Plot 11 was the same or higher than most other plots at both the 0-5 cm and 5-40 cm depth.

Preliminary mineral XRD analyses and visual color changes (Figure 4) suggested that there might be a gradient in varying mineral content of the soil as one progressed towards Plot 12 from Plot 10. However, the pattern depicted in Figure 18 detects no gradual gradient, but instead indicates that there is a rather sharp change in mineralogy somewhere between Plot 11 and Plot 12. The XRD pattern of the Plot 10 and Plot 11 samples in fact are very much alike.

It was considered that perhaps lower surface cover on both Plots 11 and 12 contributed to higher runoff and soil loss rates, but this also was not found to be the case (Figure 24). It was believed perhaps that fine roots explained differences in runoff between Plots 1-10 and Plots 11-12, but as discussed in the previous section, this was not found to be the case. Even the mean for Plot 12, 0.80 g/kg was greater than those of Plot 2 and 3 at the 5-40 cm depth.

1. Aggregate Size Distribution

Aggregate size distribution parameters indicated the aggregate stability of Plot 12 was less than that of Plots 10 and 11 for the 0-10 cm depth, yet no significant differences were found between Plot 10 and Plot 11 (Table 24). However, for the thin 0-0.5 cm surface layer, Plot 10 aggregates were 77% larger than 2 mm diameter compared to 62% for Plot 11. The surface aggregation in Plots 11-12 may explain some of the decreased infiltration rate on Plots 11-12. The DSA properties for all plots may not be identical.

2. Bulk Density and Macroporosity

As discussed in Chapter 4, analyses of bulk density (BD) was prompted by the belief that a sort of hardpan existed in Plot 12 and possibly Plot 11 that did not exist in other plots. Given the soil's very good structure and its DSA properties, it was thought that plots tilled deeper were better structured for higher infiltration rates.

Taking the area of Plots 1-10 as a single treatment (referred to as T:1-10) versus Plot 11 and 12 each as a treatment, BD data indicated there was no difference between the 0-10 and 10-20 cm depths within T:1-10. Nor was there any difference between T:1-10 and Plots 11 or 12 at the 0-10 cm depth. But T:1-10 was found to be only a little less dense at the 10-20 cm layer than either Plots 11 or 12 (Figure 19). When effective macroporosity (EM) was compared among the 3 treatments, T:1-10 was found to have an EM volume 1.6 times that of either Plots 11 or 12 (Figure 20). It is important to note that Plots 11 and 12 were found to be significantly lower than the area encompassing Plots 1-10, but not necessarily lower than each of those plots.

A second set of data made very similar findings (Tables 20-22). In the second set of BD data, EM for each plot increased by about 10% of total volume over the 1st set of data, probably because these samples were taken when it had not rained for 1 day. The first samples had been taken within 6 h of the end of the 11/6/88. This is a particularly interesting find because macroporosity is known to correlate strongly with infiltration rates, better than total porosity or many other physical properties such as bulk density and particle size distribution. One of the more widely used tests to characterize hydraulic conductivity is to measure soil moisture at various soil tensions. The method used here to determine EM is a similar test except one in which soil tension is not controlled carefully or precisely known.

Although clearing by bulldozing was not the most desirable method of clearing, it did not have the effect on soil physical properties as is usually reported elsewhere, increasing bulk density and decreasing infiltration rates (Chapter 3). But in this study the site was subsequently disked and seems to have created a very stable structure on this particular soil. Disking and raking created conditions of not only breaking up the more compacted structure of the soil but allowed the soil to be even more exposed to drying. Additional BD samples, taken near Plot 12 where there was no clearing and disking, had a low bulk density, 0.69 g/cc (Table 23 and Figure 21). In a nearby location that was bulldozed but not disked, BD predictably increased, to 0.88 g/cc. Yet EM also increased, though only slightly. Normally, it would be expected that macroporosity would decrease when BD increases. When the soil was bulldozed and disked, BD decreased but more importantly EM increased from 26% to 39%. The disking coupled with the soil's DSA properties may have actually increased macroposity in the plowed layers despite increasing BD, subsequently increasing infiltration rates.

The basic argument discussed before that tillage and exposure have interacted with the soil mineralogy to develop a very stable and excellent soil structure, allowing high infiltration rates, applies here also. However, Plots 11 and 12 have only been tilled to about 10 cm depth. The resulting effect of higher infiltration rates by tillage simply extends to a much lesser depth than in Plots 1-10. No parameters were found to be consistently different between plots with runoff, Plots 11-12, and plots with no runoff, Plots 1-10, except EM and 0-0.5 cm surface aggregates. Both decreased EM and surface aggregates are probably important in explaining the occurrence of runoff in Plots 11-12, but there is inadequate evidence to make any statistically confident conclusions. However, I believe the effects of deeper disking on to be the most important factor explaining why Plots 1-10 had no runoff, when Plots 11-12 had runoff.

C. <u>Why was there such greater soil loss, and runoff to a much lesser extent, on Plot 12 than Plot 11?</u>

This question asks not only why was runoff and soil loss higher on Plot 12 than Plot 11, but why the soil loss difference is so much greater than the runoff difference. Runoff on Plot 11 was 60% of Plot 12 but soil loss on Plot 11 was less than 3% of Plot 12. Before continuing it should be emphasized again that while there is great confidence in the accuracy of the soil loss results, there is less in the runoff results, as discussed in Chapter 4. Many of the same parameters already discussed are analyzed. The general hypothesis is that disking effects explain only differences in runoff between Plots 11-12 and Plots 1-10, but 1 or more other parameters explain differences in runoff and soil loss between Plot 11 and Plot 12.

As discussed earlier, no significant differences were found between wet bulk density, dry bulk density, and EM at either the 0-10 or 10-20 cm depth between Plot 11 and Plot 12 (Figures 19-20, and Table 19). The measured means were nearly identical. There is no evidence to support the hypothesis that differences in tillage preparation caused differences in runoff between Plot 11 and Plot 12.

It was thought that perhaps organic matter in Plot 11 may be sufficiently higher than in Plot 12 and led to better soil structure and lower runoff and soil losses. But a measured lower mean value of organic carbon (2nd set of organic carbon data) in Plot 12 was not found to be statistically significantly less than Plot 11 at any depth (Tables 15-16 and Figures 16-17). Even if the differences were assumed to be real, they are relatively small. Unless the effect of changes in organic matter on the K factor when organic matter is high is of a very large negative coefficient, it is unlikely that organic matter explains the vast difference in soil loss between Plot 11 and Plot 12.

1. Mineralogy

As commented on earlier, the XRD patterns of Plot 10 and Plot 11 are nearly identical (Figure 18). However, the XRD pattern of Plot 12 indicates a relatively sharp increase in halloysite and a decrease in goethite relative to Plots 10-11. The increase in halloysite indicates that the soil on Plot 12 is less weathered than Plot 11. It is very possible that Plot 12 is an already eroded site and much of its A horizon has been removed. One theory, discussed in Chapter 3, is that the smaller negatively charged halloysite particles pack tightly with positively charged goethite, reducing macroporosity and infiltration. Although the mechanism is not well understood, halloysite is associated with increasing a soil's erodibility.

It should be emphasized here that estimating amounts of mineral content in soils from XRD analyses is not always a very reliable technique. It is very difficult to prepare a representative sample for the analyses. The same sample X-rayed 3 different times can produce 3 different results. Jones (personal communication, 1989) states that an experienced technician can only estimate within 10-25% of the amount of any single mineral present in a soil. It should also be noted again that the results depicted in Figure 18 are from unreplicated samples and have been not been subjected to any statistical analyses.

2. Aggregate Size Distribution

As discussed already, the aggregate parameters of Plot 10 and Plot 11 at the 0-10 cm depth are very similar to each other, but both plots differ from Plot 12 (Tables 24-27). Percent weight aggregates greater than 2.00 mm diameter and MWD were both found to be significantly lower in Plot 12. The percent weight aggregates less than 0.10 mm was also found to be 2.5 times as high in Plot 12 than the other 2 plots. Admittedly, levels of aggregates less than 0.10 mm is low in all 3 plots, but clay-sized particles are known to have a much stronger affect on soil properties at small percentages than any other size particles, as is accounted for in standard soil textural classification classes. Pores filled with small sized particles fill pores, could decrease macroporosity, although this effect is not reflected in Figure 20.

This data correlates with the XRD patterns and is expected assuming an increase in halloysite in Plot 12, suggesting that the increase reduces the aggregate stability of the soil. Although increased halloysite might be expected to raise the net negative surface charge, delta pH is nearest zero in Plot 12 (Table 14). Assuming that soils with near net 0 charge tend to flocculate more, the lower negative charge was unexpected and unexplained.

3. Roots

Plot 11 was found to have a markedly higher and statistically different fine root content, 9.5 times, at the 0-5 cm depth than Plot 12 (Figure 26). Differences in root content at a lower depth were much smaller, but for soil loss control the upper depth seemingly would be expected to be much more important. Larger root content in the soil was found to be also much higher in Plot 11 than in Plot 12 (Table 35), but statistically less significant.

The drastic difference in soil loss strongly correlates with the fine root content. Fine root content in the surface soil is believed to have held and bonded soil aggregates together. The aggregates were held loosely in the sense that they were not held in a dense structure but in a formation with large interspaces. When fine roots were separated from the soil in the laboratory, it was found that many of the roots were tightly bonded to soil aggregates. Frequent flooding of dry soil samples did not remove all roots. It was necessary to dry the soil first and crush and break up the aggregates held together by the roots before they could be removed by flooding. Organic compounds or living material on the root surfaces may have played a role in bonding the roots to soil aggregates (Chapter 3). It appears that roots that have not been disturbed or removed from the soil after clearing continue to stabilize the soil structure for at least a short period of time. Fine root content on our plots, 1.8-5.6 T/ha (assuming BD to be .79 g/cc) for Plots 1-11 at the 0-5 cm depth, is relatively very high, even after bulldozing. This is considerably higher than those taken from a Costa Rican rainforest (Chapter 3).

Although it clearly appeared that fine roots were holding aggregates together I do not believe they played a major role in the aggregation of primary soil particles. Although there was an increase in fine root content in Plot 10 over Plot 11, no corresponding increase in aggregation was detected at the 0-10 cm depth.

4. Surface Cover

It was considered that surface cover was lower on Plot 12 than Plot 11, making Plot 12 more susceptible to erosion. As described in Chapter 4, a t-test initially did not find a particularly significant difference between Plot 11 and 12 in plant matter alone, but only with combined plant matter and rock cover. When a paired t-test was used to compare the means, a real difference was found highly probable. Both plant matter and rock thinned out towards the top section of each plot, presumably because bulldozing and disturbance by disking and raking had moved plant matter and rocks toward the bottom of the plot.

The combined surface cover for the whole of Plot 11 and Plot 12 was 7.2 and 3.6 percent respectively (Table 29). The difference between the two means is small, but the small difference in surface cover should not be disregarded as even a little surface cover is very effective in reducing soil loss (Chapter 3). This fact, however, has already been taken into account. Using Dissmeyer and Foster's (1981) new subfactor tables, the absolute difference of 3.6% in surface cover between the 2 plots only translated into a predicted 8% reduction in soil loss in Plot 11 (Table 4), a value that does not come near to accounting for the vast differences in actual soil losses. According to the literature, there is no strong argument that the reduction in surface cover affected differences in runoff between Plot 11 and Plot 12.

VII. SUMMARY

A. Summary of Conclusion to Question 1: Why was there no runoff or soil loss on Plots 1-10 and considerably less on Plots 11 and 12 than would be predicted by the USLE model?:

Plots 1-10 had no or essentially no soil loss because there was no runoff and the reason there was no runoff was because the soil had been disked which created a loose, porous, yet very stable soil structure. This was possible because of the soil's unique aggregating properties due to high organic matter content and particularly, its mineralogy. The soil also exhibited DSA properties that allowed the soil surface to be exceptionally well aggregated and resistant to disintegration.

B. Summary of Conclusion to Question 2: Why was there considerable runoff on both Plots 11 and 12 when there was none on Plots 1-10?:

Plots 11-12 were not disked as deep as Plots 1-10. The soil at lower depths was thus not restructured to be better aggregated. The soil below the 10 cm depth stayed wetter, had lower macroporosity, and acted as a a kind of hardpan relative to the soil of other plots at the same depth. Thus, these plots more easily saturated. I do not believe that their surfaces significantly slaked or sealed, although the aggregate data for the upper 5 mm surface of Plots 11-12 suggested that their surfaces may have impeded infiltration more than that of Plot 10.

C. Summary of Conclusion to Question 3: Why was there such greater soil loss, and runoff to a much lesser extent, on Plot 12 than Plot 11?:

It is riskier to generalize about the causes of the differences in runoff and soil loss between Plot 12 and Plot 11 because so many factors varied. There simply is a lack of control of the various parameters. There is a tendency for surface cover, organic matter, and aggregate properties to all be more conducive for soil loss in Plot 12 than Plot 11. However, the very large reduction in soil loss on Plot 11 is believed to be primarily due to its high root content, particularly the fine roots. The roots held the aggregates together and prevented them from being eroded.

The higher rate of runoff in Plot 12 relative to Plot 11 is believed to be caused by poorer aggregation both at the 0-10 and 0-0.5 cm depth, due perhaps partially to lower organic matter content but probably more importantly to the increased content of halloysite in Plot 12.

D. Adjustments to C and K Subfactor Values

Returning to the USLE model, an attempt will be made to assign new numbers to various factors. The assignment of numbers is not meant necessarily to provide accurate values for future research or reference. The purpose is to recognize the relative value of variables which have reduced soil loss to less than might be originally predicted and to help in identifying the reasons soil loss was less than expected. Only the values of K and C are in serious question (as discussed in Chapter 2).

The measured soil loss fraction of the predicted soil loss of Plot 12 was .046. Because absence of either the good soil physical properties or tillage would probably substantially increase the potential for erosion, .046 is designated an interactive subfactor of both C and K. This factor is an additional factor to the originally assumed K value of .10. If there was no tillage and exposure, 0.10 may normally be a reasonable estimate of K.

The difference in soil loss between Plot 12 and Plot 11 is 37 times and is attributed mostly to the higher fine root content, although mineralogy differences could be be responsible for increased runoff on Plot 12. The new C subfactor for root binding effect is .027 and is used as a rough estimate for Plots 1-10 also. The recalculated C value for Plot 11 is .014, much lower than the initially assumed value of .43 (Table 4). The roots in this soil are either much higher in content than those examined by Dissmeyer and Foster (1981) or have a much greater effect on reducing soil loss.

The USLE predicted soil losses for Plots 1-10, 330-370 T/ha, were far higher than measured. The C tillage and K interaction subfactor for Plots 1-10 is 0.00065, rather than .046 for Plots 11-12, because they were disked deeper, and thus their effect is greater on reducing soil loss. Adjusted USLE index values are presented in Table 36.

Table 36. Adjusted USLE factor estimates for Plots 1-12.

Plot	R	LS*P	K*C:tillage	Initial K	Adj C
1-9	1935	6.6	.00065	.10	.012
10	1935	6.3	.00065	.10	.011
11	1935	5.8	.046	.10	.014
12	1935	6.4	.046	.10	.48

These factors are only estimates, and could be considerably different. The C*K interactive subfactor for Plots 1-10 could actually be much lower because the little soil loss that did occur appeared to be primarily due to splash of just a few soil particles and aggregates at the bottom of the plots. It is conceivable that storms would have to be considerably far more intense than occurred during the year before runoff occurred. Even for Plot 12, runoff did not occur until EI30 exceeded 50 kN/h. On the other hand, the S index value temporarily contributes to overestimating soil loss because the effect of slope on soil loss is nearly mute when runoff does not occur. This would suggests that the adjusted total product of the C and K factor may actually could be underestimated.

Conclusions answering the 3 objectives are stated with partial and incomplete supportive data. Unfortunately, the experiment was not designed to explain the actual runoff and soil loss patterns. If there were numerous plots which experienced varying amounts of runoff and soil loss, the data could have been analyzed in a multiple regression, but the very few treatments allow for too few degrees of freedom.

APPENDIX I

Conversion from Metric to English Units for the USLE Model:

The procedure to calculate EI30 in English units is the same as with the metric system with the following exceptions:

1. Rainfall units should be in inches, not centimeters.
2. Use the following equation for calculating energy for intensity rather than Equation [6]:

$$KE/cm = 916 + 331 * LOG(intensity).$$

To convert from Metric units to English units or vice versa, use the following conversion ratios:

English		Metric
1.000 t/acre	=	2.242 T/ha
1.000 EI30 (100 ft-t/acre)	=	1.735 EI30 (kN/h)
1.000 K	=	1.292 K

OR

English		Metric
0.446 t/acre	=	1.000 T/ha
0.576 EI30 (100 ft-t/acre)	=	1.000 EI30 (kN/h)
0.774 K	=	1.000 K

APPENDIX II

Two pits 150 cm deep and three pits 35 cm deep on the experimental site were examined and described by Saku Nakamura of the Soil Conservation Service in Hawaii on 6/14/89.

Soil Classification: Halii series. Very fine, sesquic, isohyperthermic Anionic Acrudox. An Anionic Acrudox is defined as a soil with a net positively charged soil layer 18 cm or thicker within 125 cm of the surface, is not dry less than 90 days of the year, and is highly weathered.

General location: Island of Kauai, Hawaii. University of Hawaii Wailua Experiment Station, approximately 0.5 mile northwest of office; Alley cropping erosion experiment.

Elevation: 167 m **Annual Rainfall:** 2285 mm

Vegetation: False staghorn fern, melastoma, creeping Chinese violet, joee, pangola grass

Parent Material: Basic igneous rock **Ground Water:** Deep

Physiography: Steep side slope **Slope:** 35%

Permeability: Moderately rapid **Drainage:** Well drained

Remarks: Colors are for moist soil unless otherwise noted. All textures are "apparent field textures."

Specific location: between Plot 4 and Plot 5, halfway up slope.

Erosion: None to slight
Stoniness: 10-20% gravel in plot

Ap1 -- 0 to 20 cm; dark brown (7.5YR 3/2) silty clay, dark brown (7.5YR 4/2) dry; moderate fine subangular blocky structure; extremely hard, firm, very sticky and very plastic; many very fine and few fine roots; many fine interstitial pores; 10 percent whitish rock fragments that appear to be gibbsite; upper 1 inch has strong very fine and fine granular structure and dries irreversibly; gradual wavy boundary.

Ap2 -- 20 to 40 cm; dark brown (7.5YR 3/2) silty clay; strong very fine subangular blocky structure; very firm, sticky and plastic; many very fine and few fine roots; many fine interstitial pores; clear wavy boundary.

Bo1 -- 40 to 50 cm; dark reddish brown (5YR 3/3) silty clay; moderate fine and medium subangular blocky structure; firm, very sticky and very plastic; common very fine roots; feels gritty due to rock fragments; clear smooth boundary.

Bo2 -- 50 to 69 cm; dark brown (10YR 3/3) silty clay; moderate fine and medium subangular blocky structure; firm, very sticky and very plastic; common very fine roots; common very fine pores; few thin clay films in some pores; pocket of rock fragments that look like gibbsite; clear wavy boundary.

BC1 -- 69 to 135 cm; variegated dark grayish brown (10YR 4/2), brown (10YR 4/3), and dark brown (7.5YR 4/2) silty clay; moderate fine and medium subangular blocky structure; friable, very sticky and very plastic; few very fine roots; common very fine pores; 5 percent gravel size weathered rock fragments; gradual smooth boundary.

BC2 -- 135 to 152 cm; variegated dark grayish brown (10YR 4/2) and dark brown (10YR 3/3) silty clay; weak medium subangular blocky structure; friable, very sticky and very plastic; few very fine roots; common very fine pores; 10 percent highly weathered gravel and cobbles.

Specific location: just left of Plot 12, half way up slope

Erosion: Moderate
Stoniness: None

Remarks: This appears to have had more erosion than Plot 4 and 5. Ap2 horizon has 50% of mixture from B horizon. No gibbsite noted. This plot had most erosion - 27 T/ha.

Ap1 -- 0 to 12 cm; dark brown (7.5YR 3/3) silty clay, brown (7.5YR 5/4) dry; moderate fine subangular blocky structure; extremely hard, firm, very sticky and very plastic; many very fine and few fine roots; many fine interstitial pores; upper 1 inch has strong very fine and fine granular structure and dries irreversibly; 3% gravel; gradual wavy boundary.

Ap2 -- 12 to 33 cm; dark brown (7.5YR 4/4) silty clay mixed with 50 percent reddish brown (5YR 4/4) silty clay from the underlying horizon; strong fine and weak fine and medium subangular blocky structure; firm, very sticky and very plastic; many very fine and few fine roots; many fine interstitial pores; clear wavy boundary.

Bo1 -- 33 to 68 cm; dark brown (7.5YR 4/4) silty clay; moderate fine and medium subangular blocky structure; firm, very sticky and very plastic; common very fine roots and few fine roots; common very fine pores; 3 percent gravel; gradual smooth boundary.

Bo2 -- 68 to 89 cm; dark reddish brown (5YR 3/4) silty clay; moderate fine and medium subangular block structure; firm, very sticky and very plastic; few very fine and fine roots; common very fine pores; 5 percent gravel; clear smooth boundary.

Bo3 -- 89 to 114; dark brown (7.5YR 4/4) silty clay; weak fine and medium subangular blocky structure; friable, very sticky and very plastic; few fine roots; many very fine pores; 5 percent gravel; gradual smooth boundary.

C -- 114 to 155 cm; variegated dark brown (7.5YR 4/4), yellowish red (5YR 4/6) and very dark gray (7.5YR N3/) highly weathered rock that crushes to silty clay; massive; firm, sticky and plastic; few fine roots; common very fine pores.

Specific location: just left of Plot 11, halfway up slope.

Erosion: None to slight
Stoniness: None

Remarks: 0.73 T/ha soil loss. Surface contains 2% gibbsite and rock fragments.

Ap1 -- 0 to 35 cm; dark brown (10YR 3/3) silty clay; dark brown (10YR 4/3) dry; strong very fine subangular blocky structure; many very fine roots; common false staghorn fern stems.

Specific location: just right of Plot 11, halfway up slope.

Erosion: None to slight
Stoniness: None

Ap -- 0 to 35 cm; very dark brown (10YR 2/2) silty clay; strong fine subangular blocky structure; many very fine roots; 2 percent gibbsite and rock fragments.

Specific location: between Plot 10 and Plot 9, halfway up slope

Erosion: None to slight
Stoniness: 2 percent gravel size gibbsite and rock fragments

Remarks: No runoff during 9" storm.

Ap -- 0 to 32 cm; dark brown (7.5YR 3/2) silty clay; strong very fine subangular blocky structure; many very fine and few fine roots; few false staghorn fern stem; 2% gibbsite and rock fragments.

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